A TWO-WAY RADIO COMMUNICATIONS TRAINING PROGRAM

LESSON SA-1
TRANSISTORS

Semiconductor Materials

MOTOROLA TRAINING INSTITUTE

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Semiconductor Materials

—one of a series of lessons on two-way FM communications—

MOTOROLA TRAINING INSTITUTE
4501 W. AUGUSTA BLVD., CHICAGO 51, ILLINOIS
APPROVED BY THE STATE OF ILLINOIS
DEPT. OF REGISTRATION AND EDUCATION

PREFACE

This is one lesson of a complete Motorola Home-Study Course which presents to the Service Technician both the principles of operation and the maintenance of two-way FM radio systems. The program covers mobile, portable and base station equipment, including the latest transistorized units.

SEMICONDUCTOR MATERIALS

LESSON SA-1

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NOTICE

Diagrams and figures referenced in text are "fold-outs" in back of each lesson, for use while studying. The Examinations are also there.

Fire departments were among the first to make use of "Handie Talkie" portable radiophones. Units provide co-ordination of all fire fighting groups at the scene of large fires.

SEMICONDUCTOR MATERIALS

Lesson SA-1

Introduction

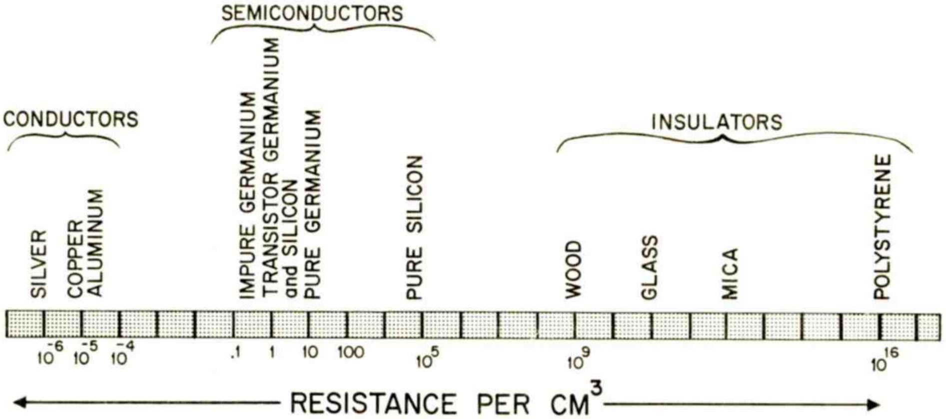
The transistor is a small, lightweight, efficient and highly-reliable device which can perform many of the functions previously assigned to the vacuum tube. The name TRANSISTOR is coined from its operating characteristic--that of a TRANSfer-resISTOR. The material from which the transistor is made is inherently neither a good conductor nor a good insulator--it is semiconductor material. Before proceeding with our study of the transistor, it is well that we first inspect the characteristics of conductors, insulators and semiconductors.

Conduction

Semiconductors do not conduct as well as metals, but they are better conductors than insulators. They are solid materials, and germanium and silicon are the elements most commonly used for transistor construction. (In our discussions of transistors we will speak directly of germanium types, but the same principles apply equally well to silicon devices.) In order to understand the nature of conduction, we must inspect closely the atom and determine why certain materials are better conductors than others.

Figure 1 represents the internal structure and electrical system of a hydrogen atom, the simplest of all atoms. It is generally agreed by physicists that the hydrogen atom has one proton, a positively charged particle, and one electron, which has a negative charge. The atomic number of an element corresponds to the number of protons or electrons in each of its atoms. Thus, hydrogen has an atomic number of one--it is element number one.

In figure 1, the proton (which is always in the nucleus) is shown by a plus sign; the electron is represented by a negative sign. This electron moves around the nucleus in an orbital manner. The term "shell" is commonly used to describe the paths or the areas occupied by electrons. The negative charge of each electron is equal to the positive charge of each nuclear proton, with the result that the atom is in electrical balance--its net electric charge is zero.



The Elements are Often Classified as Conductors, Semi-Conductors and Insulators, According to their Electrical Resistance.

Figure 2 depicts the probable construction of the helium atom. Here there are two protons in the nucleus and two electrons in the first shell--helium is element number two. This atom is also in electrical balance, for there are the same number of electrons as there are protons. In fact, in every atom there is the same number of electrons and protons, so all atoms are normally electrically neutral.

Carbon atoms, illustrated in figure 3, have six protons and six electrons--the atomic number is six. As always the protons are in the center or nucleus, and they are represented by the "plus 6." Again the electrons are orbital about the nucleus, but we find that there are two separate shells. Each shell has a certain number of electrons required in order to fill that shell.

For example, the first shell accepts only two electrons. Eight electrons fill the second shell, while the third shell needs eighteen. For the carbon atom, then, two electrons completely fill the first shell and the remaining four electrons are found in a second shell. The electrons in the outer shell of any atom are called "valence" electrons. Thus, the carbon atom has 4 valence electrons.

We are now ready to determine the condition within the atom which allows it to be conductive or nonconductive. Simply, it depends upon the electrons in the outer ring or shell of the atom. In some atoms, these electrons are loosely tied to the atom and may be readily displaced from atom to atom by an electric field. This is the nature of conduction and electricity. Thus, atoms whose outer-shell electrons are easily moved from atom to atom are good conductors.

Conversely, other atoms have outer-shell electrons which are tightly bound, with the result that these electrons are not readily moved from atom to atom. These materials are insulators.

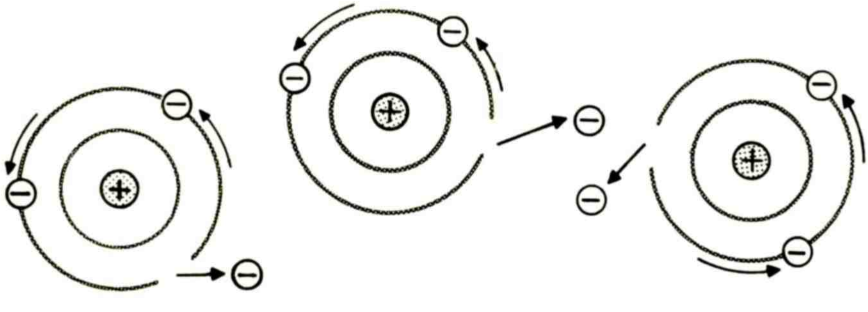
Figure 4 is a representation of an aluminum atom. There are a total of 13 protons and 13 electrons, making aluminum element number thirteen. The first two electron shells are filled with 2 and 8 electrons respectively, and the remaining three electrons are found in the third shell. These outer-shell electrons are readily moved from atom to atom, so the material is a good conductor.

We now have a relatively good picture of the nature of conductivity. If electrons are loosely held and hence capable of being easily moved from atom to atom, the material is a good conductor. When electrons are tightly bound to the atoms, however, the material is an insulator. We are ready to look at the atoms of semiconductors.[1]

Semiconductors

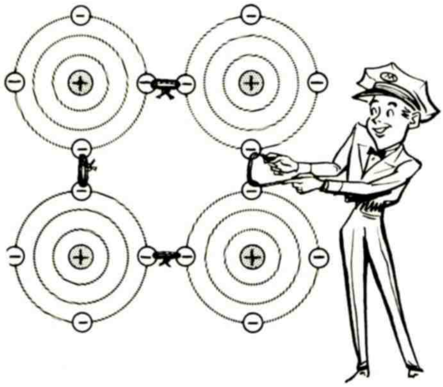
Germanium and silicon, the materials from which most semiconductor devices are made, are tetravalent. This means that there are four (valence) electrons in their outer-most shells. For germanium, these 4 electrons are in the fourth shell; in silicon atoms the 4 electrons are in the third shell. Figure 5 shows the electron arrangement of the silicon atom.

In addition to the fact that there are four electrons in the outer shells and being "in between" the conductors and the insulators, intrinsic (pure) germanium and silicon material is in a crystalline or lattice form which further restricts the movement of the electrons. The effect of this upon the ability of the material to conduct can be seen from figure 6, the representation of the crystalline structure of germanium (or silicon). The small circles represent the nuclei of the atom. The "+4" in each nucleus indicates the 4 protons which counteract (electrically) the 4 valence electrons.



Conduction or Non-Conduction of an Element Depends Primarily Upon the Number of Free or "Valence" Electrons in the Outer Electron Shell.

1. See Basic Theory and Application of Transistors (TM11-690) pages 5-18.



Certain Elements Form Crystalline Structures in Which the Valence Electrons are Held in Place by "Covalent Bonds."

Each of the atoms is equidistant from four other atoms, and is held fast in its position by covalent bonds, a "sharing" of valence electrons by adjacent atoms. These covalent bonds are represented by lines between the atoms. Each electron forms a bond with one of the valence electrons of a neighboring atom so that all of the valence electrons are captured in covalent bonds. These bonds are very stable and strongly bind the electrons to the individual atoms. As a result, there are but few free electrons which may be utilized for current. It seems, then, that this crystal would be a good insulator--and it is, in this intrinsic form. We will now determine what happens when electrons periodically escape from their bonds as shown in figure 7.

Due mainly to thermal agitation, an electron will occasionally gain sufficient energy to escape from its covalent bond. This electron then "wanders" through the material in a haphazard way; there is no scheme to this motion. The path may eventually end near the point where it started, in which case the electron recombines with the atom from which it originated.

When an electron escapes from its covalent bond, it leaves behind it an atom which is no longer electrically neutral, for there are now fewer negative electrons than there are positive protons; that atom becomes a positive ion. See figure 8.

The positive ion has the same amount of electrical charge as the electron, but it is positive in nature. In addition, the ion is fixed in its position in the crystal lattice structure and cannot move about as does the electron. This positive ion represents a "hole" in the structure, a hole that can be satisfied only by the capture of an electron. There is a great attraction for an electron, and any which might wander into the vicinity will be pulled into the hole, once more bringing about a balance.

It is not unusual that a hole will attract an electron from a nearby covalent bond, leaving a similar hole where the electron was pulled from. In this manner the hole may be thought of as moving about in the crystal; the ion doesn't move but, by interchanging electrons, the location of the positive hole changes. This action is often referred to as "hole conduction." This hole movement by an interchange of electrons is a source of electric current.

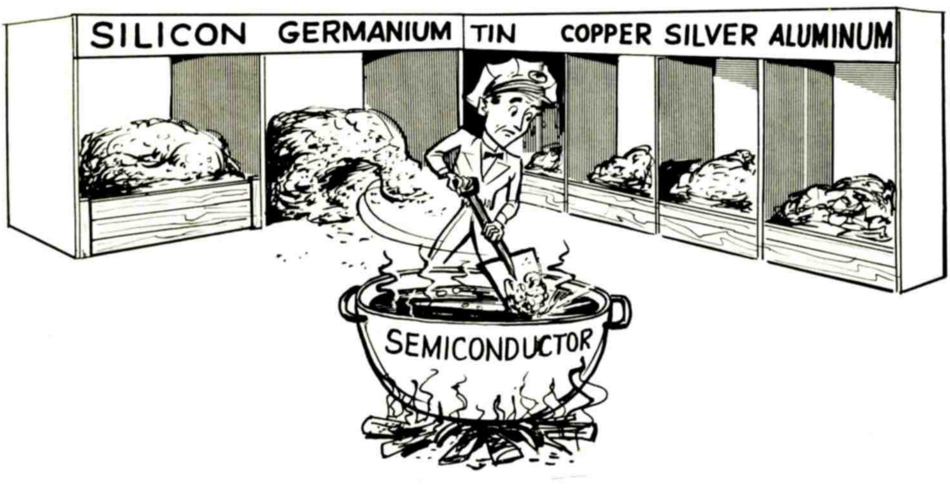
From the above discussion, we see that in the pure semiconductor material (germanium or silicon) the electrons are tightly bound by covalent bonds which prevent any great amount of current through the crystal. Some electrons do break their bonds, however, and they are available for a limited amount of conduction. In the absence of any external force, their motion is haphazard throughout the crystal. They eventually recombine with a positive ion.

An electron breaking from its bond leaves a "hole" which effectively moves about in the material to provide a second source of conduction. As the temperature of the material is increased, the electrons have additional energy; more of them break free from their atoms and are available for conduction. More holes are also present. Higher temperatures thus increase the conductivity of semiconductor materials.[2]

Transistors and other semiconductor devices are not made of the intrinsic material we have been discussing. Instead, a small number of "impurity" atoms are added in order to change the conduction characteristics, as we will now see.

N-Type Semiconductors

A small number of certain impurity atoms substituted for germanium atoms in the otherwise intrinsic germanium crystal greatly changes the conduction ability of the crystal. We will consider first the addition of a pentavalent



Germanium and Silicon are the Materials Most Commonly Used for Making Semiconductors.

2. Sec TM11-690, pages 19-21.

"N-Type" Semiconductor Material is Made by Adding a Small Amount of Arsenic or Antimony--Materials Which Have 5 Valence Electrons--to Germanium or Silicon.

material such as arsenic or antimony. (These are called pentavalent because they have five valence electrons in their outer shells.) When a very small number of these atoms are introduced into the germanium crystal (the actual number is usually in the order of 1 in 10 million or less), the crystal takes the form shown in figure 9.

The impurity atom becomes part of the crystal, being located in the position which otherwise would belong to a germanium atom. Four of the electrons in the outer shell of the impurity atom form covalent bonds with electrons of the surrounding germanium atoms, but there is no atom to form a covalent bond with the fifth electron. This leaves the electron free to move about in the crystal. Furthermore, there is no corresponding hole (due to an incomplete covalent bond) created in the crystal by this electron moving about, so that each impurity atom of the crystal provides a free electron.

The conductive properties of the crystal may be controlled by the number of impurity atoms introduced. When the electron leaves the vicinity of the impurity atom, the electrical system of the atom is no longer balanced, for there are more protons than electrons. The atom is a fixed positive ion, for it is not free to move about in the crystal as is the released electron.

The number of free electrons in the crystal doped with pentavalent material is much greater than for the intrinsic material. Because pentavalent doping produces free electrons within the crystal structure, the material has a negative characteristic--the current established in the crystal will be due to the motion of these electrons. For this reason, it is common to refer to this material as an N-type semiconductor. Because they "donate" electrons to the crystal structure, pentavalent atoms are often called "donors."

P-Type Semiconductors

We will consider now the effect on introducing into the germanium crystal a small number of trivalent atoms, such as indium, aluminum or gallium. These materials are called trivalent because their atoms have three valence electrons in their outer shell. Again the number of impurity atoms within the germanium crystal is very small. The crystal formation shown in figure 10 results.

Each impurity atom (we will assume indium for convenience) is surrounded by four germanium atoms. Three electrons are available in the outer shell (of the indium atom) to enter into valence bonds with neighboring atoms, but there is no electron to complete the fourth covalent bond. Because there is no electron to complete the crystal covalent bond structure, we have a "hole."

This hole exhibits a great attraction for an electron, so in effect we have a positive hole--there is need for another electron. In fact, it is not uncommon for an electron associated with a nearby atom to be pulled into this hole, leaving a hole at the atom from which the electron was removed. Thus, the hole effectively moves about in the crystal. One such hole is created for each impurity atom added to the crystal.

Without an applied external field, the movement of the holes within the crystal is haphazard. With an applied field, however, the drift of these holes is consistently toward the negative point, and current (by hole conduction) is established. These holes are then considered to be the carriers, the means of establishing current in this P-type semiconductor. The indium atoms are commonly referred to as "acceptors," for they capture any electron in the vicinity.

By pulling an electron into the crystal structure, an acceptor atom becomes negatively charged, for there are now more electrons associated with the atom than there are protons in the nucleus. Such negative ions are fixed by their covalent bonds and cannot move through the crystal structure.[3]

3. See TM11-690, pages 21-30.

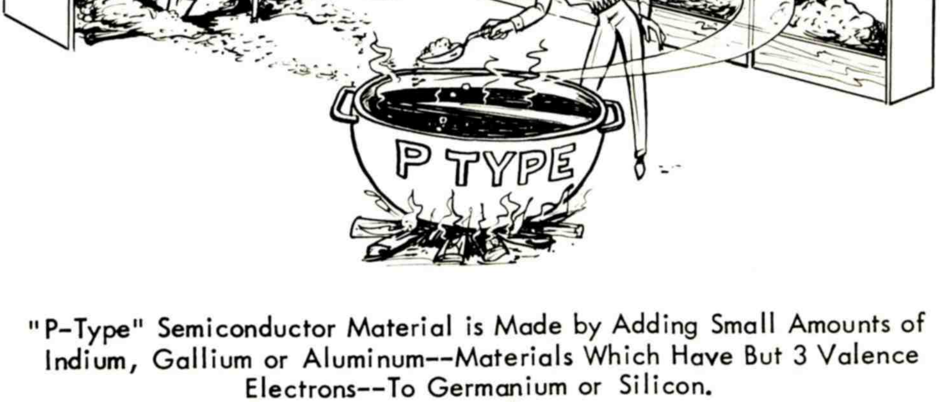
Majority and Minority Carriers

Regardless of whether a semiconductor material is of the N or P type, both electrons and holes are available to be used as carriers. This is caused by the electrons breaking away from their covalent bonds. In most cases, these electrons and holes recombine so that the main conduction is due to electrons or holes created by the impurity atoms. For N-type material, then, we consider the electrons as being the majority carrier or means of conduction, and for P-type material the holes are considered as the majority carriers. In N-type material there are always a few holes, so they are the minority carriers, and electrons are considered as minority carriers of P-type materi-

Conduction Within N-Type Materials

Before leaving the subject of conduction, let us see the effects of applying voltages to both N and P semiconductors. We will start with the N type--see figure 11.

In figure 11A, the voltage source makes the right side of the material negative and the left side positive. The free electrons (the majority carriers in N material) are attracted to the left or positive side. There will be current in the complete circuit as shown; this current is measured by the meter. The amount of current is determined by Ohm's Law ($I = E \div R$), in which case the R is the effective resistance of the semiconductor



"P-Type" Semiconductor Material is Made by Adding Small Amounts of Indium, Gallium or Aluminum--Materials Which Have But 3 Valence Electrons--To Germanium or Silicon.

Electrons leaving the crystal at the left side are replaced by electrons entering the crystal at the right. While this action constitutes the majority of the current in the circuit, there is a small amount of current due to minority carriers (holes) moving in the opposite direction. Hole current is always considered to move in the circuit from the positive side of the material to the negative side (the "conventional" direction of current).

In figure 11B we find the same piece of N material but with the battery polarity reversed--the positive side of the battery is now connected to the right side. The action is the same as before, but the electrons are attracted to the right side of the material and the holes to the left. The ammeter must now be connected with the polarity shown. From this action we see that the N-type semiconductor material is capable of conducting current equally well in either direction. As we shall see in the next lesson, conduction in one direction only (rectification) is realized only when a junction is made of P and N materials.

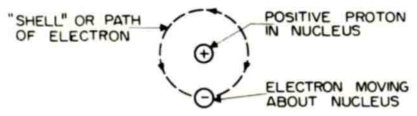
Conduction Within P-Type Material

Figure 12 shows the conduction within P material when an external voltage is applied. At 12A the battery makes the left side of the crystal positive with respect to the right side. In the external circuit between the battery and the semiconductor, we consider the current as corresponding to the electron flow, from the negative side of battery to the semiconductor and from the semiconductor back to the positive side of the battery.

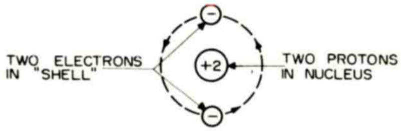
Within the semiconductor, however, the current is due mainly to a movement of "holes," which are the majority carrier. Holes move internally from the positive side to the negative side, from right to left. If we wish to correlate this action with the movement of electrons, we can remember that the movement of holes in the material is due to electrons being interchanged from one atom to the next, in which case the electron drift is in the direction opposite to the hole movement. The ammeter in figure 12A records the circuit current, and again the amount is determined by the applied voltage and the resistance of the material.

Figure 12B uses the same P material, but the applied voltage has reverse polarity. The holes inside the P material are attracted to the left side, so that the circuit current is now reversed. Reversing the battery polarity doesn't change the amount of current in the circuit, it merely changes the direction.

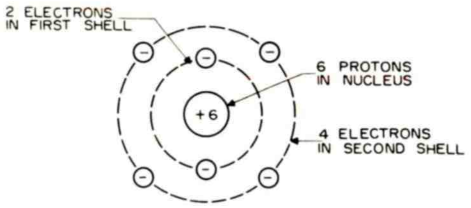
We have seen the nature of the conduction within N- and P-type semiconductors. In the next discussion we will continue with the study of semiconductors made into P-N junctions (diodes).



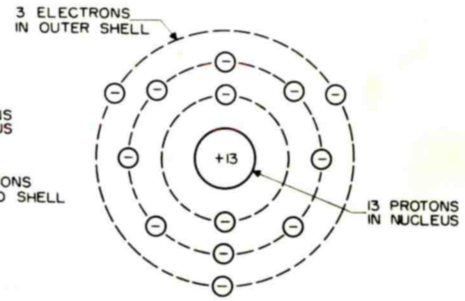
HYDROGEN ATOM
FIGURE 1



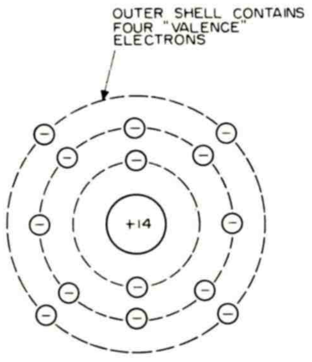
HELIUM ATOM
FIGURE 2



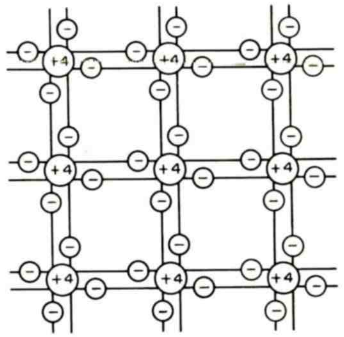
CARBON ATOM
FIGURE 3



ALUMINUM ATOM
FIGURE 4



SILICON ATOM
FIGURE 5


GERMANIUM CRYSTAL DIAGRAMMETICAL SKETCH. FIGURE 6

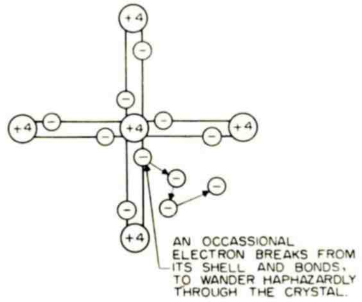


FIGURE 7

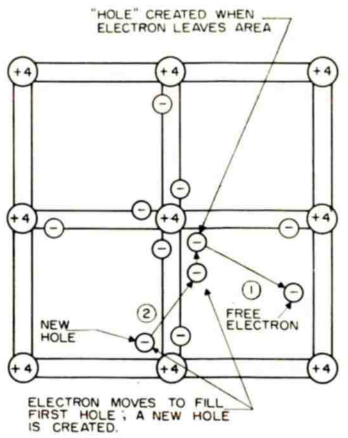
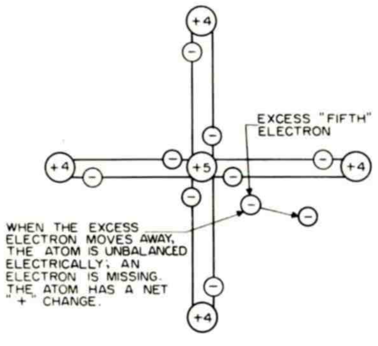
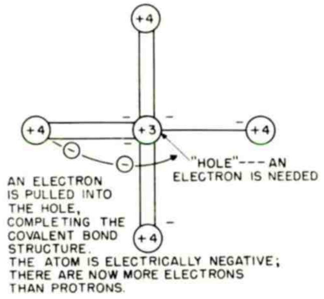


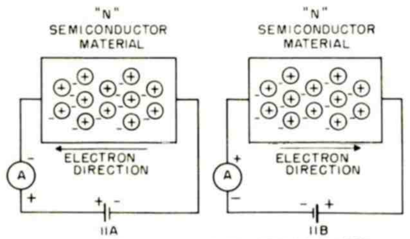
FIGURE 8



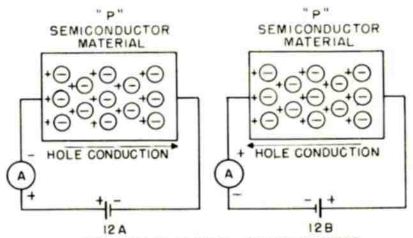
"N" DONOR ATOM IN GERMANIUM CRYSTAL
FIGURE 9



"P" ACCEPTOR ATOM IN GERMANIUM CRYSTAL
FIGURE 10



CURRENT IN N-TYPE SEMICONDUCTOR
FIGURE 11



CURRENT IN P-TYPE SEMICONDUCTOR
FIGURE 12

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Germanium and Silicon Diodes

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SILICON AND GERMANIUM DIODES

LESSON SA-2

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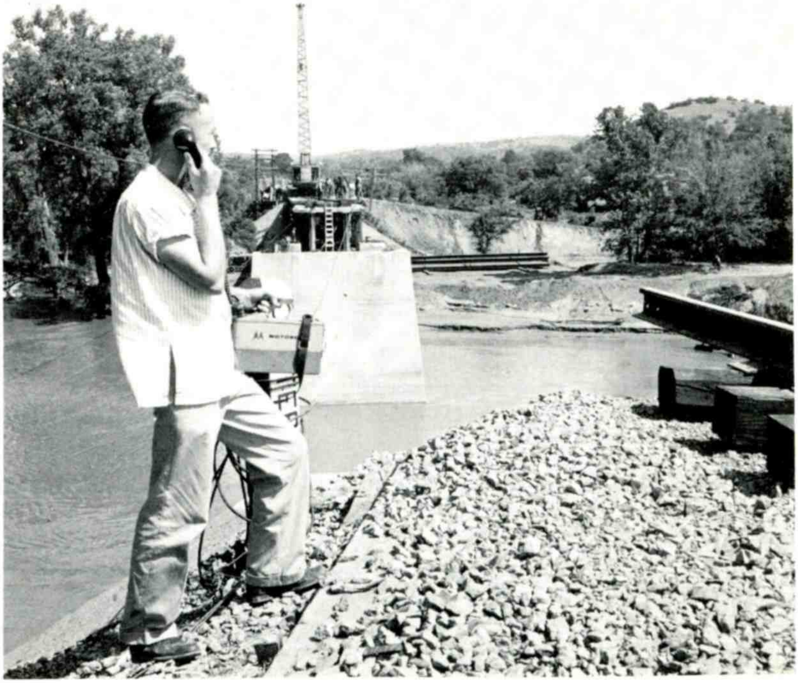


Construction foremen can communicate throughout project area when equipped with portable radiophones. Through extensive use of transistors such instruments are lightweight and low in power drain.

SEMICONDUCTOR DIODES

Lesson SA-2

Introduction

In the preceding lesson, we studied the nature of semiconductor materials which have been "doped" by P and N impurity atoms. We found that in the N-type semiconductor the impurity atoms provide a supply of free electrons, which become the current carriers; in P-type semiconductors, the added impurity atoms create a deficiency of electrons, leaving "holes" in the structure, which become the carriers.

In this lesson we shall study the nature and operation of semiconductor diodes. Two such diodes are possible, the junction diode and the point-contact diode. We will start with the junction diode.

The Junction Diode

When a junction is made of P-type and N-type semiconductor materials, we have a device possessing rectifying characteristics similar to those found in vacuum tube diodes. This device is called a "junction" diode. For the main part these diodes are used where high current levels are involved, as in power supplies.

As a start, we will assume that a block of P-type material is brought into contact with a block of N-type material. See figure 1. (In practice, junctions are not formed in this manner, but it well illustrates the action which takes place.) When the two materials are first brought into contact an interaction occurs between the carriers. Before we can understand how this junction rectifies, it is necessary to determine the exact nature of this initial action and the condition of the carriers after the junction has been formed. See figure 2.

At the left in figure 2 we find the P material with its "holes." The N material with its excess electrons is at the right. When the junction is formed, the holes and electrons at the surfaces of the materials combine. That is, electrons move across the junction and into the P material, and the holes cross the junction to reach the N material. When this occurs, fixed ions are "uncovered" on the right side of the junction, for there are now too few electrons to produce a balanced electrical condition. On the left side of the junction, the negative fixed ions of the crystal structure are evidenced. These ions are fixed within the lat-

Adjoining Layers of P and N Semiconductor Materials Produce a P-N Junction: this is a Semiconductor Diode.

tice structure of the crystalline materials; they are unable to move about.

The fixed negative ions at the left of the junction repel the free electrons at the right. At the same time, the positive ions at the right side have a repelling effect upon the positive carriers in the P material at the left.

In addition, the fixed positive ions on one side of the junction and the fixed negative ions on the other side of the junction produce an electric field across the junction, the same as a charged capacitor sets up an electric field in its dielectric material. This electric field, called the "barrier field," means that a voltage exists across the junction. This field discourages any further exchange of carriers across the junction and the area occupied by the uncovered ions is known as the "depletion area."

Before any further action can take place, it will be necessary either for the electrons on the right to have sufficient energy or force to overcome the field set up in the depletion area, or for the holes on the left to be "helped" across the junction by some external energy source. This can be accomplished by applying a voltage to the junction, and this voltage must have the proper polarity, as illustrated in figures 3 and 4.[1]

Reverse Bias

In figure 3, the positive side of the battery is connected to the negative or N material, and the negative side to the positive or P material. As soon as the voltage is applied, we again have an initial action taking place. Electrons within the N material are pulled away from the junction, toward the positive terminal of the battery. This uncovers more fixed positive ions near the junction.

Holes within the positive P material are attracted to the negative battery terminal, uncovering additional fixed negative ions at the left side of the junction. Due to the greater number of fixed ions at each side of the junction, we have a stronger barrier field existing at the junction, and the depletion layer

1. See Basic Theory and Application of Transistors (TM11-690), pages 30-33.

is also wider. It is now more difficult for carriers to cross the junction.

Thus, when a voltage of the polarity shown in figure 3 is applied to a P-N junction, it is more difficult to establish current across the junction than it is without the applied voltage. This voltage is commonly referred to as a "reverse bias." The polarity is easy to remember when we recall that the positive side of the battery goes to the N material and the negative side of the battery to the P material--the polarities are "reversed."

While there is usually some current across the junction even when it is reverse biased, this current is very small and may be disregarded for our present discussion. (As we shall soon see, too much reverse bias can break down the junction structure and cause a high reverse current.)[2]

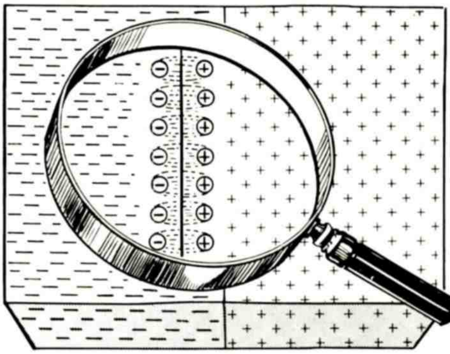
Forward Bias

Forward bias has the exact opposite effect upon the current across the P-N semiconductor junction. Instead of opposing any movement of carriers across the junction, forward bias encourages junction current. Figure 4 shows forward bias.

The components of figure 4 are the same as those of figure 3. The only difference is that the battery connections have been reversed, and the ammeter will show considerable current. In order to provide forward bias, the positive side of the battery goes to the P material and the negative side of the battery to the N material. Let's see what is happening at the junction.

The battery tends to produce a field at the junction which opposes the barrier field created by the fixed ions. The external voltage actually only reduces the internal field so that the electrons on the right side of the junction readily move across the junction into the P material and continue on to the positive side of the battery. The holes at the left side also have sufficient energy to cross the junction.

The depletion layer is greatly reduced and represents but a minimum amount of resistance. The current is thus high, being limited by the number of carriers in the N and P material, the size of the junction, and the applied voltage.[3]



At the P-N Junction, the Fixed Charges Produce a "Barrier Field" Within the Depleted Area.

2. See TM11-690, pages 33-34.
3. See TM11-690, pages 34-35.

Diode Current Characteristics

We have already seen that forward bias produces current across the semiconductor diode, but reverse bias produces little or no current. The curve in figure 5 illustrates the magnitudes of these currents in relationship to the bias voltage.

With forward bias, the current increases according to the amount of applied voltage. The only point that is appreciably curved is at the very low values of forward bias. The amount of current produced is determined to a very large degree by the size of the junction and the intensity of the impurity atoms in the N and P sections. Larger junctions and a higher percentage of impurity atoms increase the current capability of the diode.

While there is little or no current through the diode with reverse bias, it is well to see the characteristics of this current. In figure 5 we see that a small value of current is present with reverse bias, and this current does not change as the bias is increased. That is, there is no noticeable increase until the point of junction "breakdown" occurs. The reverse current in the junction then suddenly increases to a high value. This is due to the breakdown of the covalent bonds within the crystal structure at the junction, releasing a large number of free electrons and holes for current conduction.

As soon as the excessive reverse bias is removed, the junction returns to its original condition (provided that the junction has not been damaged by heat). If the crystal structure has been damaged, the unit will no longer be efficient as a rectifier.[4]

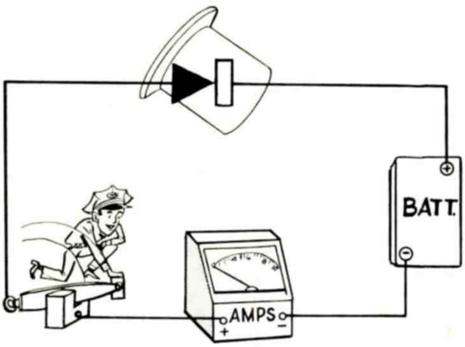
Symbols

The accepted symbols for semiconductor diodes are shown in figure 6. The P material is represented by the arrow and the N material by the line. As shown, the arrow may or may not touch the N line, but this has no significance as far as the symbol is concerned.

The arrow indicates the conventional direction of current, from positive to negative. Electron movement through the diode is in the opposite direction. Figure 7 points out these two "directions of current" in a circuit. It matters not which direction is assumed, for the circuit currents and voltage drops are unchanged.

For example, look at the resistor in figure 7. Following the conventional positive to negative direction, the current enters the resistor from the bottom and leaves at the top. Using this direction of current the bottom is positive and the top is negative. If electron flow is assumed, the current is from the top down through the resistor, but here the side the electrons enter is negative so again the top is negative and the bottom positive. Thus, the difference is only in the viewpoint taken and does not change what takes place in the circuit.[5]

4. See TM11-690, page 35.
5. See TM11-690, page 42.



Reverse Bias Applied to the Semiconductor Diode Does Not Produce Current at the Junction.

Half-Wave Rectifier

One common use for the semiconductor diode is as a half-wave rectifier, shown in figure 8. Here we find an AC source, a rectifier, and a load. The arrows show the direction of conventional current, from positive to negative. During the positive alternation of applied current, the upper terminal of the generator is positive with respect to the lower terminal; the voltage applied to the diode is a forward bias, with the result that the diode is conductive.

The amount of current is determined mainly by the value of the load resistance and the applied voltage. The resistance of the diode is relatively small compared to that of the load, so the internal voltage drop of the diode is very small and for all practical purposes the full source voltage appears across the load.

During the next alternation, the upper terminal of the generator is negative with respect to the lower terminal; this voltage applied to the diode is a reverse bias and there is no circuit current. Thus, there is no voltage across the load, and all of the voltage appears across the diode.

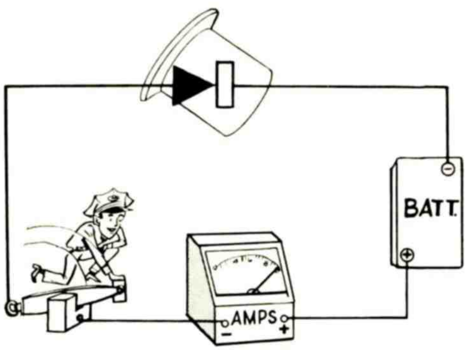
The action taking place in figure 8 is no different from that in a vacuum tube diode rectifier circuit. The internal voltage drop of the semiconductor diode is usually less than that of the vacuum tube, however, with the result that the output voltage (load voltage) is greater. Other advantages are found in the efficiency, ruggedness, reliability and size of the semiconductor diode. Silicon diodes are perhaps the most popular type of semiconductor rectifier used today.

Full-Wave Rectifier

A full-wave rectifier is normally preferred to a half-wave rectifier. Figure 9 is a typical example. A transformer secondary winding is center-tapped and diodes connected in series with the load rectify the AC voltage to DC.

At A, we see the action when the applied AC makes the upper terminal of the secondary positive with respect to the bottom. Considering each half of the secondary, the upper terminal is positive (with respect to the center tap) while the bottom terminal is negative.

The upper diode is now forward biased and conducts through the load resistor, producing a voltage with the right side being positive. During this time the lower diode is reverse biased and nonconductive. Thus, during the first alternation the upper diode rectifies the voltage of the upper half of the secondary and this voltage appears across the load.



Forward Bias at the Semiconductor Diode Causes Current Through the Junction.

At B, we see the action during the second half-cycle. The lower secondary terminal is positive and the upper terminal is negative. The lower diode is now forward biased and conducts through the load, once more making the right terminal positive. During this second alternation, the upper diode is reverse biased and nonconductive.

From the above, we see that each alternation of the applied voltage causes one of the diodes to be conductive. The waveforms show that each alternation appears across the load.

Full-Wave Bridge Rectifier

Another semiconductor rectifier circuit commonly found in two-way communications equipment is shown in figure 10. Here the transformer secondary has no center tap. The rectifiers operate from the full secondary voltage and the full secondary voltage appears across the output.

During the half-cycle when the applied voltage is positive at the top of the winding, rectifiers CR1 and CR4 are forward biased and allow current as shown by the solid arrows. The current through the load makes the right side positive. During this time, rectifiers CR2 and CR3 are reverse biased and nonconductive.

During the second half-cycle, when the bottom of the transformer is positive, rectifiers CR2 and CR3 are forward biased and become conductive--the direction is shown by the broken arrows. The current is through the load in the same direction as before, making the right side positive.

Types of Junction Diodes

Two main types of construction are used for junction diodes, the grown junction and the fused junction. See figure 11.

The grown junction is represented at figure 11A, and here we see what appears to be a block of N material and a block of P material placed together. This is not the actual method of manufacture, however. Instead, we start with one type of material, usually "N." When the crystal is partly grown, the characteristic is changed by adding some P impurities to the mixture. The rest of the crystal, then, is made of P-type material. Large contacts are made to each end of the crystal to complete the diode.

The fused junction diode is made in a different manner. A small bead of P impurity material (usually indium) is placed on an N-type wafer. See 11B. This assembly is placed in an oven for a specific period of time and heated to a temperature at which the P atoms fuse into the N wafer, producing P-type germanium at the surface of the wafer. This produces a P-N junction between the indium and the N wafer.

Point-Contact Diodes

A second type of semiconductor diode is called "point-contact." These diodes are restricted to low current applications, but their characteristics are such that they become very useful at higher frequencies, particularly the very high frequencies where vacuum diodes are no longer practical.

Figure 12 illustrates the internal construction of a point-contact diode. The active elements are the crystal wafer and the "cat whisker." The metal base makes good contact with the crystal and the cat whisker has a direct connection to the second external lead. The parts are enclosed in insulating material to protect them from moisture and the assembly is then encapsulated.

The symbol for the point-contact diode is the same as for the junction diode (figure 6). The long line or bar indicates the crystal element (which is the cathode) and the arrow is the cat whisker (which is the anode). If we analyze current through this unit, the conventional direction will be represented by the arrow, from anode to the cathode. Electron flow is opposite to the direction of the arrow, from cathode to anode.

The point-contact diode is usually made from a thin wafer of N material and a beryllium-bronze wire. In the manufacturing process, current is pulsed through the contact and supposedly produces a P region in the wafer, directly under the metal point (the exact action is not completely known). An extremely small P-N junction is thus formed. Due to the very small dimensions of this junction, the unit has very little effective capacitance and provides efficient operation at high frequencies. In addition, the junction transit time is short, for improved high-frequency operation.

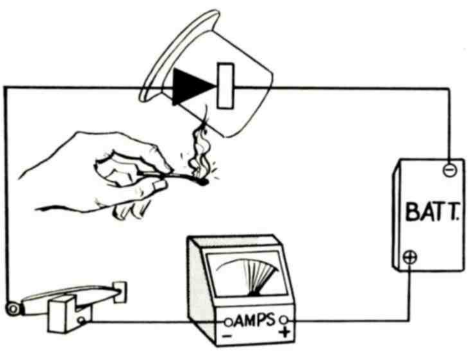
Point-contact diodes are made of both germanium and silicon. Originally the silicon type were more satisfactory for high-frequency application, but recent improvements have made the germanium diodes useful in applications such as high-frequency mixers or detectors. The point-contact diode is used extensively where low forward resistance and a small reverse current are desirable. Typical applications are as second detectors, discriminators, limiters, and clippers. Figure 13 shows two typical circuits for point-contact diodes.[6]

6. See TM11-690, page 5, also see "Understanding Semiconductor Diodes," reference S-2.

Silicon Diode Applications

In addition to their use as power rectifiers, silicon diodes provide certain services not possible with vacuum tubes or germanium devices. These are due to the inherent forward current and reverse current properties of silicon junction diodes. In the forward direction, the current does not increase beyond a fraction of a microampere until the voltage reaches as much as .3 or .4 volt. In the reverse direction, the current is again very low until a certain breakdown voltage is reached, at which time the reverse current increases rapidly to a maximum value.

Both of these pecularities are also evidenced in the germanium diode, but the action is more gradual with the amount of applied voltage. In addition, the stability and reliability do not approach that achieved with the silicon diode.



An Increase in Diode Temperature Causes an Increase in Diode Current.

We shall now look at these two characteristics more closely and see how they become useful. Let us start with forward current.

In figure 14, we see a typical forward-current curve for a silicon diode. As the forward voltage increases from zero, the current remains at a fraction of a microampere until the voltage reaches 0.3 volt. With greater voltages, the current rises to a relatively high value, the amount depending upon the voltage.

We are not interested in the value of current which is produced by these higher voltages, but in the fact that the current is very low up to the point of about 0.3 volt and then suddenly rises to a high value with greater voltages.

Figure 15 is a practical circuit for protecting a sensitive meter from excessive overloads by connecting a silicon junction diode in parallel with the meter movement. (Assume that this diode has a forward current characteristic similar to that shown in figure 14.)

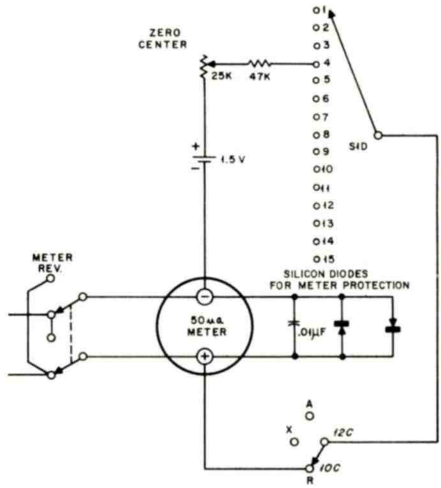
The meter sensitivity is 50 microamperes, and the internal resistance is 2000 ohms. Applying Ohm's Law (E = I X R), the voltage across the meter at full-scale deflection is 0.1 volt. This means that when the meter is at full-scale deflection, the voltage across the diode is also 0.1 volt.

Looking at the curve of figure 14 for this diode. With 0.1 volt applied, the current will be a fraction of 1 microampere and the meter sensitivity will be virtually unaffected by the current through the diode. If the diode were to conduct any appreciable amount of current, the meter reading would not be accurate, for much of the current would be bypassed around the meter.

Meter protection is provided when we consider an overload of the meter, in this case a three-to-one overload. When the current is 150 ua, the voltage across the meter is 0.3 volt, and the diode is at the point where it is about to conduct. Any further increase of current will place the diode at a point of high conduction; any further increase of current will thus be through the diode rather than through the meter. Once the meter current has reached a certain maximum amount, additional current will be through the diode with very little additional increase through the meter.

Meter movements are built to withstand a certain amount of overload current, and a diode is selected which will conduct or bypass the current around the meter before reaching the value of current which will damage the meter.

Improved protection of the meter (the maximum allowed meter current is closer to its rating) is possible by adding a resistor in series with the meter movement as shown in figure 16. Here the added resistor is 2000 ohms, doubling the



Here We See the Protective Diode Meter Circuit of the Motorola Test Set.

resistance of the meter branch. Now 50 ua through the meter will cause a total drop of 0.2 volt across the diode. For an overload of 2 to 1, the voltage across the diode will be 0.4 volt and the diode will be in full conduction. For this arrangement the meter current will never be greater than 100 ua, which is only a 2-to-1 overload.

Higher values of resistance will bring the diode closer to conduction for full meter deflection and given even closer protection, but the diode current under adverse conditions is likely to shunt appreciable current around the meter before full-scale current is realized. Among the most adverse of these conditions are high temperatures.

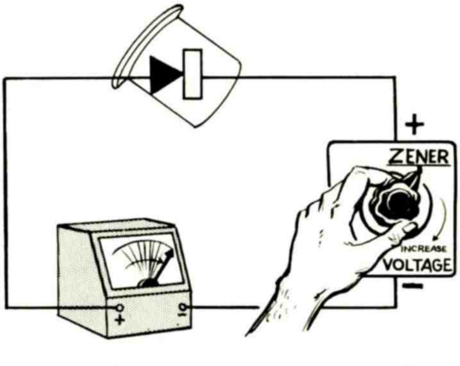
Where it is desirable to protect the meter from overload current in both directions, it is practical to connect two diodes in parallel with the meter, one in each direction (figure 17). When the circuit current makes the upper terminal positive with respect to the lower terminal, diode D1 will protect the meter (as already explained for figures 15 and 16).

Diode D2 affords protection from excessive currents through the meter in the opposite direction. The leakage current through the reverse connected diode is negligible. The arrangement of figure 17 is the same as that of the Motorola Model TU 546 test set, discussed in Lesson MA-3 (figure 9).

Zener Silicon Diodes

If we refer back to figure 5, we recall that reverse bias on a diode produces little current--so very little as to be forgotten in most applications. In addition, we saw that if the reverse bias is increased to a certain point, the unit suddenly becomes very conductive and a large current is established. This current, we found was due to a breaking down of the crystal structure within the boundaries of the junction.

This is commonly called the Zener effect: diodes designed to make use of this action are called Zener diodes. At present, silicon diodes are used almost exclusively for this purpose. (Zener is pronounced ZEE'ner.)



When the Reverse Voltage at the Diode is Increased to the "Zener" Voltage, a Large Current Suddenly Occurs.

In general, we can think of a Zener diode as having the same purpose as the gas filled tube--that of maintaining a constant voltage across its terminals. While the method by which the diode achieves this goal is somewhat different from that of the gas-filled regulator tube, the overall action is the same. Look at figure 18. Here a Zener diode is used as a DC voltage regulator.

In figure 18, the diode is placed in parallel with the circuit to be regulated, but in reversed polarity. In series with the diode (and load) we find a resistor. The unregulated supply must have sufficient voltage to be equal to the desired value of regulated voltage and the drop across the resistor; in most applications the unregulated supply is several times larger than the load voltage. The supply voltage causes the Zener diode to be conductive, under which condition it maintains a constant voltage equal to its breakdown value.

Zener diodes are available with breakdown ratings ranging from a few volts to as much as 300 volts. Where higher voltages are required, several units may be placed in series, in which case the breakdown value will be the sum of the separate ratings. (For this application it is advisable to use units of similar ratings.) While the Zener diode serves the same purpose as voltage regulator types of tubes, they have the advantage that smaller voltage ratings are possible. "VR" tubes are practical only at values between 75 and 150 volts.

The Zener characteristic curve of the silicon diode shows that additional current through the diode does not appreciably change the voltage across the diode. Besides serving as a convenient means of providing voltage regulation, the constant voltage across the diode becomes a source of reference voltage. Regardless of changes of input voltage, the voltage across the diode remains relatively constant and serves as a source of known, fixed voltage. The circuit for this service is similar to that of figure 18 and is given in figure 19.

The voltage across the diode becomes a "reference" and remains steady over a relatively wide range of conditions. A known voltage is convenient for calibration of instruments, etc. The variable resistor allows adjustment for the correct current through the diode, assuring stable operation. The current must be limited to a safe value--below the dissipation rating of the diode.

The Zener diode may also be used as a means of providing an AC reference voltage of constant amplitude. Figure 20 gives a simple arrangement. The circuit is basically that of a limiter. The diodes are connected back-to-back so that one diode limits in one direction and the second diode in the opposite direction.

Operated from an AC source, during the first half cycle diode D1 conducts, the voltage rising until the Zener voltage rating of Diode D2 is reached. Both diodes are now conductive and the voltage cannot increase further. When the next alternation is applied, diode D2 is conductive but diode D1 does not conduct until its breakdown voltage is reached.

If the diodes have the same value of breakdown voltage, the positive and negative portions of the output waveform will have the same amplitude; the total or peak-to-peak voltage will be twice the breakdown value of one unit. Where the applied voltage is considerably greater than the breakdown voltage, the output waveform will be a square wave. Input voltages not reaching the Zener operation of the diodes will not produce full output voltage.

Identifying Diode Elements

One problem often encountered in service work is the identification of the anode and cathode terminals of semiconductor diodes from their markings or construction. While absolute identification is not always possible, due to inconsistencies from one unit to the next, the following generalities should help identify most of them.

Let us compare first the symbols for the vacuum tube diode and the semiconductor diode, shown as A and B of figure 21. The arrow of the semiconductor corresponds to the plate of the tube and the bar corresponds to the tube cathode. Thus, on some diodes we can logically expect to find a K, indicating the cathode. See E in figure.

Other diodes have a "+" and this also identifies the cathode terminal. This marking is justified when we remember that the cathode terminal of a diode used as a rectifier connects to the positive side of the resulting DC load voltage. (See C in the figure.)

Some diodes have neither "K" nor "+" markings, but there may be a dot or one or more color bands near one end. (See D, F. and I of figure 21.) Again this end is the cathode. Often a diode with color bands will also have a letter at the anode end, which identifies the manufacturer.

A final group of semiconductor diodes have no marking of any kind to identify the terminals, but they are built with an irregular shape at one end in order to indicate the cathode. Examples are found at G and H of figure 21.

We can summarize this discussion by saying that any identification on the semiconductor diode, be it "k," "+," a dot, color bands or an irregular shape, usually indicates the cathode.

STUDENT NOTES

STUDENT NOTES

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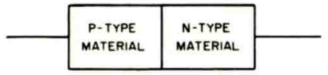
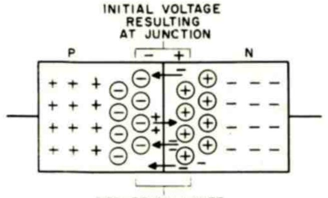
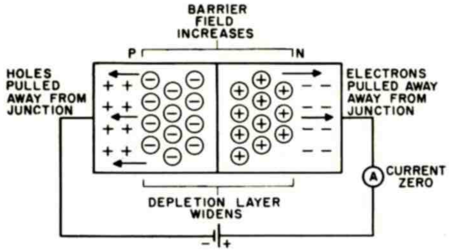


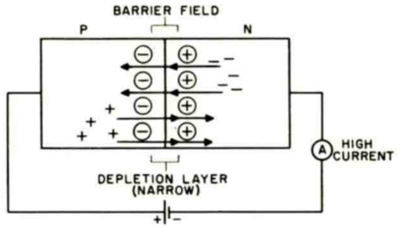
JUNCTION TRANSISTOR
FIGURE 1



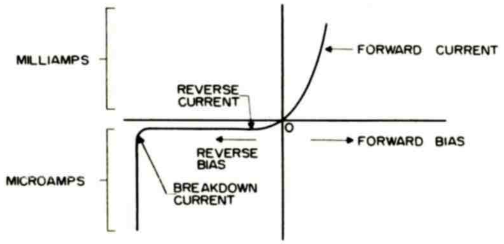
BARRIER FIELD OF JUNCTION DIODE
FIGURE 2



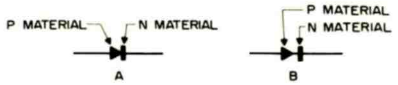
REVERSE JUNCTION BIAS
FIGURE 3



FORWARD JUNCTION BIAS
FIGURE 4



CURRENT CHARACTERISTICS OF SEMICONDUCTOR DIODES
FIGURE 5



SYMBOLS FOR SEMICONDUCTOR DIODES
FIGURE 6

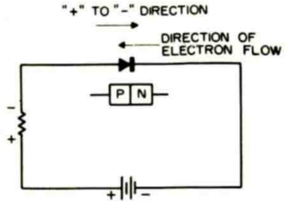
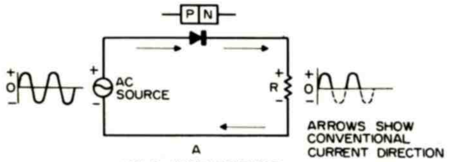
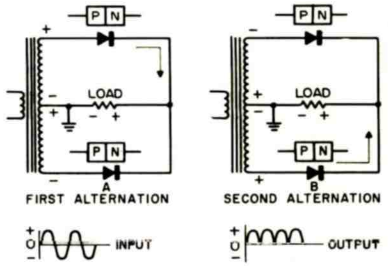


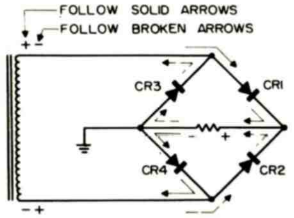
FIGURE 7



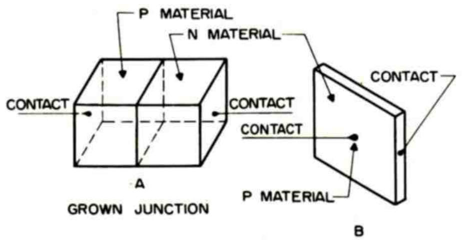
HALF-WAVE RECTIFIER
FIGURE 8



FULL-WAVE RECTIFIER
FIGURE 9



FULL-WAVE BRIDGE RECTIFIER
FIGURE 10



JUNCTION DIODE CONSTRUCTION
FIGURE 11

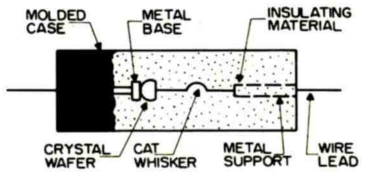


FIGURE 12

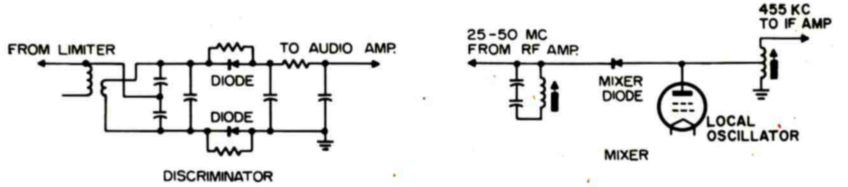
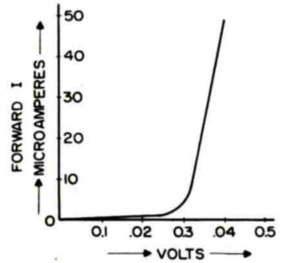
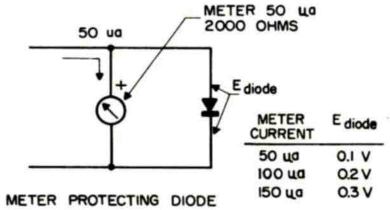


FIGURE 13



FORWARD CURRENT OF
SILICON JUNCTION DIODE
FIGURE 14



METER PROTECTING DIODE
FIGURE 15

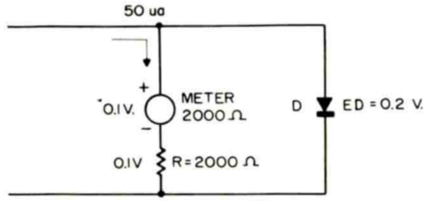


FIGURE 16

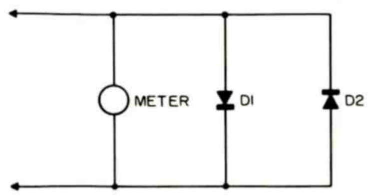
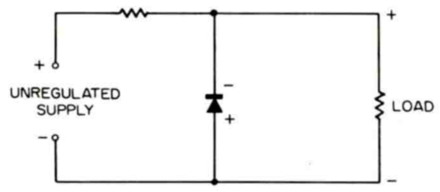


FIGURE 17



ZENER DIODE AS VOLTAGE REGULATOR

FIGURE 18

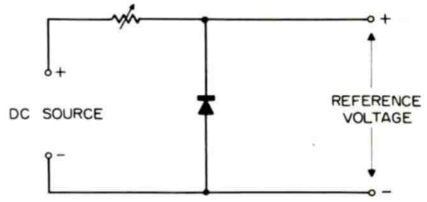


FIGURE 19

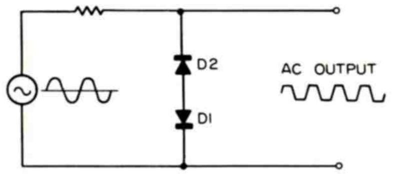
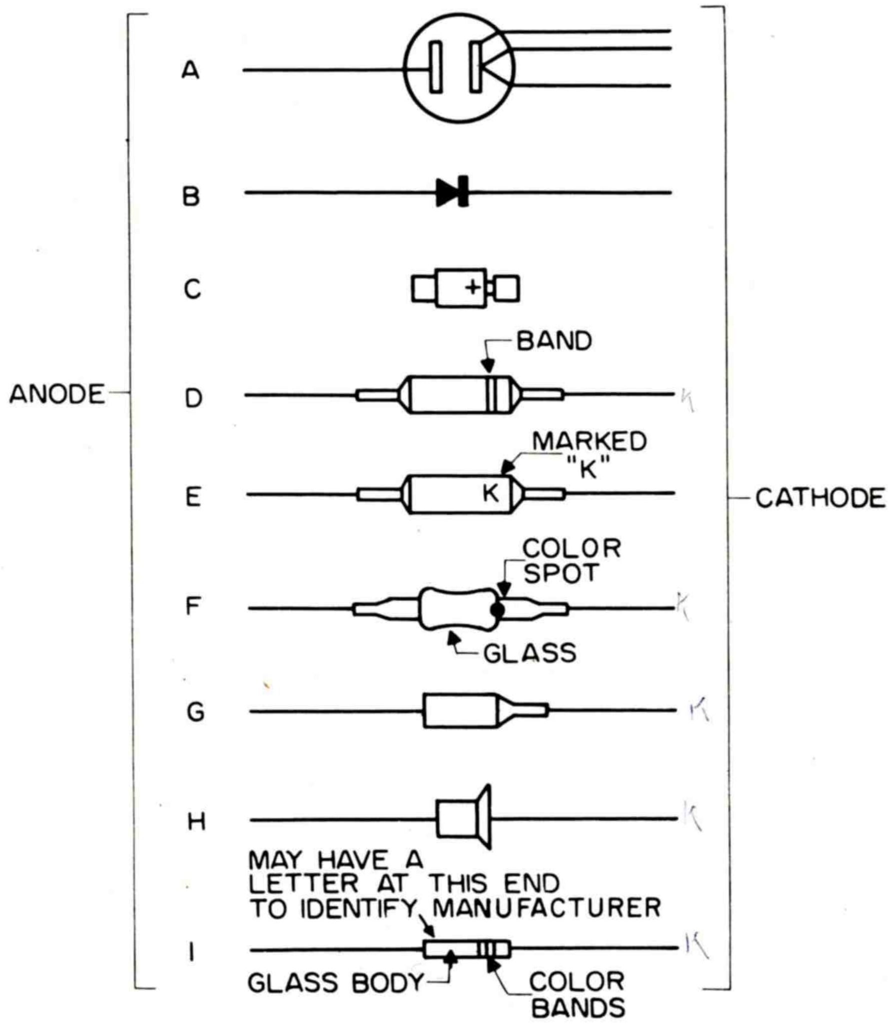


FIGURE 20



TUBE, GERMANIUM, AND SILICON DIODES IDENTIFICATION

FIGURE 21

national

MOTOROLA

RADIO COMMUNICATIONS

service

A TWO-WAY RADIO COMMUNICATIONS TRAINING PROGRAM

LESSON SA-3
TRANSISTORS

The Transistor

MOTOROLA TRAINING INSTITUTE

A TWO-WAY RADIO COMMUNICATIONS TRAINING PROGRAM

LESSON SA-3
TRANSISTORS

The Transistor

—one of a series of lessons on two-way FM communications—

MOTOROLA TRAINING INSTITUTE
4501 W. AUGUSTA BLVD., CHICAGO 51, ILLINOIS
APPROVED BY THE STATE OF ILLINOIS
DEPT. OF REGISTRATION AND EDUCATION

PREFACE

This is one lesson of a complete Motorola Home-Study Course which presents to the Service Technician both the principles of operation and the maintenance of two-way FM radio systems. The program covers mobile, portable and base station equipment, including the latest transistorized units.

THE TRANSISTOR

LESSON SA-3

TABLE OF CONTENTS

NOTICE

Diagrams and figures referenced in text are "fold-outs" in back of each lesson, for use while studying. The Examinations are also there.

Communications on oil refining apparatus is best accomplished by transistorized "Handie Talkie" portable radiophones. Maintenance and refining engineers are able to communicate with both refinery headquarters and with personnel working on the structure.

TRANSISTOR CONSTRUCTION AND OPERATION

Lesson SA-3

Introduction

In the two preceding lessons we discussed the conductivity of elements (particularly semiconductors), the doping of germanium and silicon to produce P- and N-type material, the semiconductor diode, and the nature of forward and reverse bias.

In this lesson we shall discuss the transistor, concentrating on its basic construction and operation. We shall be interested mainly in answering the basic questions, "What is a transistor?" and "How does it work?" Let us start with the construction of the transistor.

What Makes A Transistor?

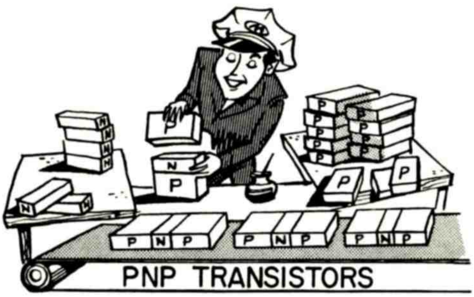
The basic transistor is a three-element semiconductor device consisting of two junctions such as those found in the diodes we have been discussing. This does not mean, however, that a transistor could be made by connecting two such diodes together. Instead, there must be a certain physical relationship between the various elements and junctions. Figure 1 illustrates the construction.

At A, we find a very thin slice of N material sandwiched between two pieces of P material. We have two separate junctions. Starting at the left, we find first a P-N junction and then an N-P junction. The N material is common to both junctions. This middle section is very thin, in the transistor, so that the outer materials (P material) are very close to each other. As we shall see, this is essential if we are to have transistor action.

At figure 1B, we find a second possible transistor combination--a thin slice of P material between two pieces of N Material. Again there are two junctions and the outer materials are physically close to each other. Transistors which resemble the arrangements of figure 1 are called junction transistors; they are constructed in the same general manner as junction diodes.

Figure 1A is commonly called a PNP transistor, and 1B an NPN transistor. The reason for these designations is obvious if we consider the arrangement of the P and N materials.

In the PNP transistor of figure 2A, the P material at the left is considered to be the source of current carriers. That is, in P-type material the holes are the main carriers, so the holes become the source of current in the same manner as the electrons at the cathode of the vacuum tube become the source of tube current. In operation, the holes of the P material at the left move across both junctions and into the P material at the right. This action occurs only when the correct bias voltages are established at the junctions.



Basically, a PNP Transistor Consists of a Thin Portion of N Material Between Two Pieces of P Material.

In the NPN transistor of figure 2B, the electrons within the N material at the left are the majority carriers; they are the source of current. With proper bias at the junctions, these carriers traverse both junctions, establishing current between the outer elements.

One particular type of transistor is said to be fabricated by the "grown" method, the characteristic of the materials being changed from P-type to N-type (or vice versa) as the crystal is grown. Another type of transistor, known as the "alloy junction," is shown in figure 3.

Here we find a thin wafer of N material. Two beads of indium (P impurity material) have been alloyed into opposite sides of the N wafer, by placing the assembly in an oven and heating it. The indium atoms alloy into the surface of the N wafer, producing two junctions within the N material.

When terminal connections are made to the three elements (the two indium beads and the N wafer), we have a practical PNP transistor. (An NPN transistor may be made in the same manner, using a P wafer and two beads of N impurity material.) Most of the PNP transistors found in equipment today are of the alloy junction type.

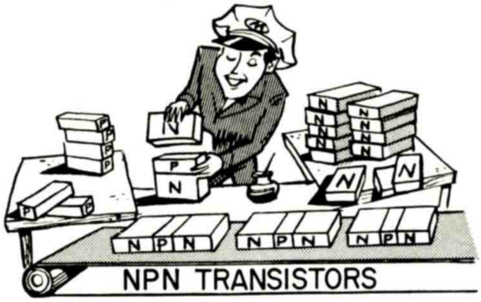
The principle of operation is essentially the same for the alloy transistor as for the grown junction type.

The Three Transistor Elements

Inspect figure 4A for the names of the three transistor elements. We said that the one at the left is the source of the carriers within the transistor. Thus, we can readily see why this element is called the "emitter."

We also said that the carriers within the transistor cross both junctions to enter the right-hand section of the unit--hence, the term "collector" is appropriate for this portion of the transistor. The third element, the center, is call the "base."

These terms apply equally well to the PNP transistor at figure 4B. The source is the emitter, the middle element is the base, and the third part is the collector. The emitter of the NPN transistor 4A is N material, the base is P material, and the collector is N material. In this transistor, current is considered to be the result of electron conduction. In PNP units the emitter, base and collector are P, N and P material, respectively, and the conduction is due to the movement of holes. [1]



Basically, an NPN Transistor is Made by Sandwiching a Thin Slice of P Material Between Two N Areas.

Junction Bias

Figure 5 shows the two junctions within the transistor. These are the emitter-base and the collector-base junctions. We often refer to them as just "emitter junction" or "collector junction," respectively.

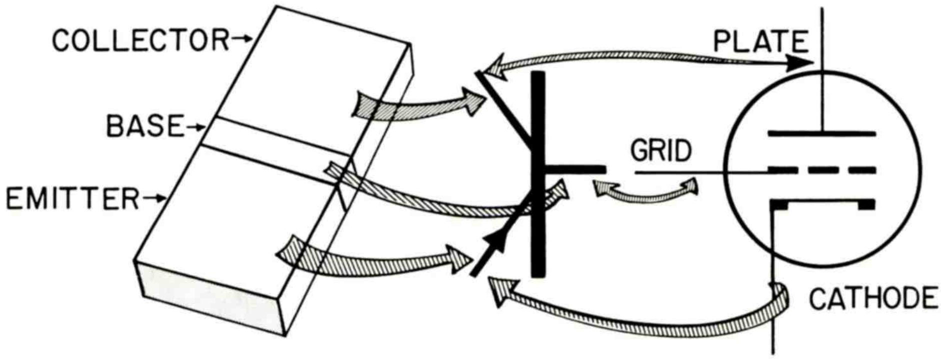
If the emitter is to become the source of "carriers" it is necessary to bias the emitter junction in the forward direction. (The action is similar to that already discussed in the preceding lesson dealing with diode junction bias.) Forward emitter junction bias is shown in figure 6.

At figure 6A, the holes--the carriers of the emitter--readily move across the emitter-base junction and enter the base region, for the base is negative with respect to the emitter and the resulting field causes the carriers (holes) to cross the junction and enter the base region. Once inside the base, however, the movement of these carriers is somewhat haphazard and they "diffuse" throughout the entire base region.

With no additional voltages applied to the transistor, the holes eventually reach the external base circuit, becoming emitter-base current. As we shall soon see, however, this is not what happens when the proper bias is established at the collector-base junction.

Before we proceed with collector junction bias, however, let us look at figure 6B, which shows forward bias at the emitter-base junction of an NPN transistor. Here the battery voltage makes the N emitter negative with respect to the P base, releasing the free electrons (the carriers) of the emitter into the base. The only difference here is that current is due mainly to electron conduction while hole conduction is the nature of the current in the PNP transistor (at figure 6A).

1. See Basic Theory and Application of Transistors (TM11-690) pages 36-39.



Here We See a Comparison of the Transistor Elements With Those of the Vacuum Tube.

Figure 7 shows the normal bias for the collector-base junction--in the reverse direction. The collector-base current is thus extremely small--practically zero. This is desirable. (The ability of reverse bias to discourage junction current has already been analyzed in our discussion of diodes.)

Now that we have given separate consideration to the forward bias of the emitter-base junction and to the reverse bias of the collector-base junction, we are ready to determine what really happens when these two biases are applied simultaneously to the transistor.

Transistor Currents

Figure 8 shows a PNP transistor with the emitter forward biased and the collector reverse biased. The forward bias of the emitter drives the holes (the carriers in a P-type emitter) across the junction and they diffuse throughout the base. Instead of reaching the base to establish an emitter-base current, however, most of the holes are captured by the collector and constitute a current from emitter to collector.

There are several reasons why the holes (the carriers from the emitter) are captured by the collector instead of the base. In the first place, the collector junction area is larger than that of the emitter--it more or less "surrounds" the emitter. (See figure 8.) In the second place, the base material is very thin between the emitter and collector, with the result that the holes entering the base do not travel very far from the junction before they encounter the electric field established at the collector-base junction by the collector-base bias.

Another reason for the large emitter-to-collector current is that the emitter material is heavily doped with impurity atoms; the N-type base material is not. This means that there are many more holes crossing the emitter junction into the base than there are free electrons in the base which can combine with the holes. As a result, most of the holes continue to wander through the base until they encounter the electric field at the collector junction.

Thus, because most of the carriers from the emitter are captured by the collector and only a small number of them reach the base terminal, the collector current will be almost as large as the emitter current and the base current will be very small.

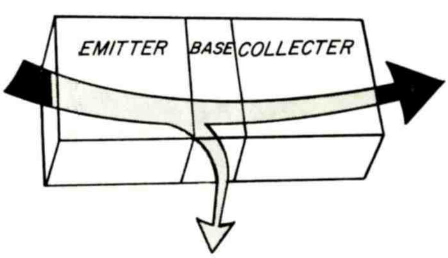
At first consideration of figure 8 it may appear that the reverse bias at the collector would prevent collector current. In fact, this is true so far as collector-to-base current is concerned. Insofar as the holes originating at the emitter but now drifting through the base are concerned, however, the collector junction bias actually encourages these holes to cross the collector junction.

Thus it is that the polarity of the collector bias (the direction of the field established by this bias) encourages holes to move from the base region to the collector. We must remember that these holes in the base are not always present in the N material; on the contrary, they start at the emitter (with the emitter junction forward biased), cross the emitter junction, and diffuse throughout the base area. The holes from the emitter (now in the base) are next pulled across the collector junction, establishing emitter-collector current.

In the absence of any emitter current, however, there are no holes (carriers) released into the base from the emitter, so there can be no collector current; collector current is dependent upon and controlled by emitter current.

Brief Review

Let us summarize briefly the main points which we have already learned about the transistor. With biases as shown in figure 8, a large number of holes leave the emitter, cross the junction and enter the base material. Also, there are many more positive holes available in the emitter than there are electrons in the base. As a result, very few of the holes are captured within the base as base current. Instead, most holes encounter the field produced by the collector bias and are swept across the collector junction.



Current Through the Transistor--From the Emitter to the Collector--is Dependent Upon and Controlled by a Smaller Emitter-Base Current.

The collector current is almost as great as the emitter current; the base current is very small compared to the collector current. Collector current, since it depends upon emitter current, is readily controlled by the emitter current; emitter current, in turn, may be regulated by the emitter-base bias.

Transistor Symbols

Figure 9 shows various semiconductor symbols which have been standardized by the IRE and adopted by the EIA. Figure 9A shows the base symbol. The horizontal line is the base proper and the perpendicular line is the base connection. From this symbol it is impossible to know whether this is N material or P material. This can be determined only after the emitter symbol has been added, as shown in 9B and 9C.

At B we find a slanted line (representing the emitter) meeting the base line. This slanted line also carries an arrow and the arrow points toward the base, indicating the emitter is P material. The slant signifies that the base must be composed of the opposite type material, so if we have a P emitter, we have an N base. At C the emitter arrow points away from the base, so we have an N emitter (and a P base).

The slanted line at D (with no arrow) represents a collector--again the slant signifies that the collector material is dissimilar to that of the base. Thus, if the base is P, the collector is N, and vice versa.

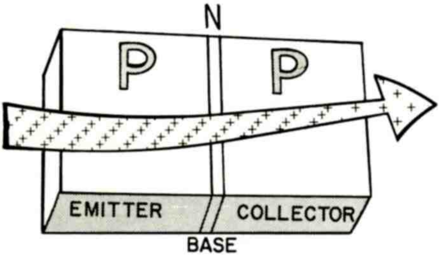
Figure 10 shows the complete symbols for both PNP and NPN transistors. At 10A the emitter arrow points toward the base line, so this is a PNP unit. At 10B the emitter arrow points away from the base line; this is an NPN unit.

Transistor Action

We have already seen that the collector current in the transistor depends upon the release of carriers from the emitter into the base. This, in turn, is determined by the emitter junction bias. While the bias for the emitter junction is often stated in terms of the voltage applied from an external source, it is well that we also think of this bias in terms of the current established at the junction.

The emitter current divides into two separate currents--the collector current and the base current. It is normal for at least 95% of the emitter current to become collector current, resulting in a relatively small base current. Thus, the collector current is many times greater than the base current, and their ratio is often used to express the current "gain" of a transistor.

Let us assume that a transistor is being used as an amplifier--also, that normal forward bias has been established for the emitter junction, and that the collector junction is reverse biased. An external signal is applied, and this



For PNP Transistors, Current is Due Mainly to the Movement of Positive Carriers (Holes) From the Emitter to the Collector.

signal causes small changes in base current. As a result, larger changes occur in the collector current. (We shall see the specific circuits later.)

The ability of the transistor to produce large changes in collector current as a result of small changes in emitter-base current is one of the factors contributing to the ability of the transistor to amplify. Another important factor which enables a transistor to provide gain is its high collector (output) impedance compared to its low emitter-base (input) impedance. More will be said about this in later lessons.

Transistor Circuits

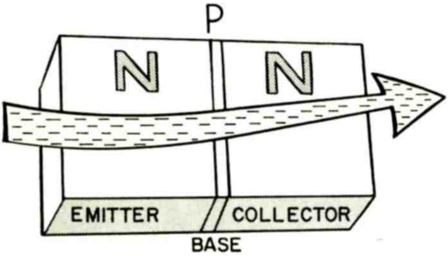
When analyzing the various configurations associated with the transistor, it is permissible to make certain comparisons with vacuum tube circuits. While the emitter, base and collector are by no means identical to the cathode, grid and plate (respectively) of the vacuum tube, they exercise somewhat similar functions. The units are compared in figure 11.

At A we find the triode tube symbol, at B we see the pictorial representation of the transistor we have been using, and at C we have the transistor symbol. (This, of course, could be an NPN as well as the PNP unit shown.) The emitter serves the same purpose as the cathode--it becomes the source of current carriers for the device. The collector is similar in function to the plate, and the base is somewhat similar to the grid.

A basic comparison may be made of the action of the transistor and that of the vacuum tube. In the vacuum tube, the grid-cathode voltage (bias) is used to control the plate current (cathode-plate current). In the transistor, the emitter-base bias becomes the factor which controls the collector current (emitter-collector current). We must always remember that emitter-base bias refers more specifically to the emitter-base current than it does to the applied external voltage.

Small variations of the grid-cathode bias voltage in the vacuum tube causes comparatively large changes of the plate current. In a similar manner, small changes of the emitter-base current means large changes of collector current. For this reason, we often refer to the vacuum tube as a voltage controlling device, but to the transistor as a current controlling device.

Figure 12 shows a popular vacuum tube circuit, the grounded cathode; the signal is applied between grid and ground, and the output is taken from the plate circuit. The corresponding transistor circuit shows the emitter grounded, with the signal applied between base and ground and with the output secured at the collector. The biasing circuits have been eliminated from both the tube and transistor circuits for simplicity.



For NPN Transistors, Current is the Result of Electrons Leaving the Emitter and Crossing the Base Into The Collector

We usually refer to the arrangement of figure 12 as a "common emitter" circuit rather than a grounded emitter. A resistor and capacitor are often included between emitter and ground--then, although the emitter is no longer "grounded," it is still common to the input and output circuits.

Figure 13 shows another tube circuit, this time a grounded-grid amplifier. The corresponding transistor circuit, which is also shown, is termed a "common base" circuit, for the base is common to the input and output. In the vacuum-tube arrangement, the signal is applied to the cathode and the output is taken from the plate circuit. In the transistor arrangement, the input is to the emitter and the output is taken from the collector.

A third familiar vacuum-tube circuit is the "cathode follower" or "grounded plate" circuit of figure 14. The signal is applied to the grid and the output taken from the cathode. The corresponding transistor circuit is the "common collector" arrangement in which the input is applied to the base and the output is taken from the emitter. In this circuit, the collector is common to both the input and the output.

The Common-Emitter Circuit

The circuit of figure 15 shows a common-emitter transistor amplifier. A 6-volt battery is used both for the forward bias of the emitter junction and for the reverse bias of the collector. This is accomplished by grounding the positive side of the battery, so that the grounded emitter is the most positive point of the circuit. The collector connects to the negative side of the battery through a resistor, RC, and for convenience we have assumed that collector current causes a drop of 4 volts across this resistor. This means that the voltage between the collector and ground is two volts, the collector side being negative.

Forward bias of the emitter junction is obtained by means of a voltage divider (R1 and R2) across the battery, the base being connected to the tap on the divider.

(The drop across R2 is 0.2 volt.) With the emitter grounded and with the base at -0.2 volt with respect to ground, a forward bias of 0.2 volt is obtained--a typical value for many transistors.

The collector junction is reverse biased by virtue of the collector being more negative than the base. The collector is -2 volts with respect to ground and the base is -0.2 volt with respect to ground, resulting in a net reverse bias of 1.8 volts between collector and base. We are now ready to see what happens when a signal is applied.

Common-Emitter Phase Relationships

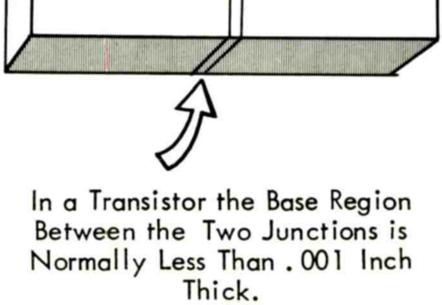
Figure 16 shows the phase relationship between the input and output waveforms for the positive half-cycle of the input signal. The initial voltages applied to the various transistor elements are the same as in figure 15.

During the first alternation, the input signal varies from zero to a positive 0.1 volt and then back to zero. When this signal is superimposed upon the base-ground circuit of the transistor, it causes the base-emitter voltage to change from its normal value of -0.2 volt to -0.1 volt. This decreases the forward bias and, as a result, the collector current as well as the voltage drop across the collector resistor must decrease.

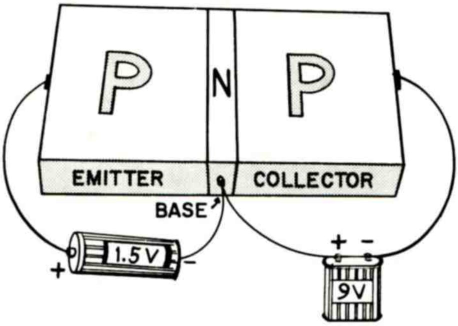
We previously assumed that the voltage across RC was 4 volts. We shall now assume further that the voltage drop across the resistor decreases to 3 volts. As a result, the collector voltage (with respect to ground) changes from -2 volts to -3 volts. At the output (on the other side of the coupling capacitor), the DC component is removed by the capacitor and all that remains is the 1-volt change in the negative direction.

Thus, for an input signal which swings in the positive direction, the output voltage swings in a negative direction. This indicates that there is a phase reversal of 180° in the common-emitter circuit. Let's see if this reversal also holds true for a negative swing of the input signal.

Figure 17 indicates the action of the same common-emitter amplifier during the negative alternation of the input signal. The input



In a Transistor the Base Region Between the Two Junctions is Normally Less Than .001 Inch Thick.



Normal Bias of a PNP Transistor Demands a Positive Emitter and a Negative Collector, Both With Respect to the Base.

swings 0.1 volt negative and causes a change of base voltage from -0.2 volt to -0.3 volt. This is an increase of the forward bias, and the transistor currents increase. The increase of collector current through the collector resistor causes a greater voltage drop, and we have assumed the increase is from 4 to 5 volts. The voltage at the collector with respect to ground has then changed from -2 volts to -1 volt. At the output, the coupling capacitor has removed the DC component and the output has swung 1 volt in the positive direction.

From this action we see that the output voltage of the common-emitter circuit is 180° out of phase during the negative swing of the input signal as well as for the positive swing. We may thus generalize, saying that the common-emitter circuit produces a 180° phase shift in the output signal.

We have assumed that the input signal of 0.1 volt in figures 16 and 17 causes changes of 1 volt at the output. Thus, the voltage amplification of 10 has been realized. In practical circuits, gains even greater than 10 are possible, particularly at low frequencies and for limited bandwidth circuits.

The term "gain," as we use it here, applies strictly to the ratio between the output and input voltages. In many discussions on transistors, gain is a term reserved for the power relationship of the output to the input, and "amplification" is used for either the voltage or the current ratios. We shall have more to say on this subject in a later lesson.

Figures 16 and 17 make use of a PNP transistor. For a comparable NPN circuit, the only noticeable differences in the circuit is that the polarity of the battery and circuit voltages are reversed. A positive swing at the input will still cause a swing in the negative direction at the output, and vice versa.

The Common-Base Circuit

Figure 18 is a simplified arrangement of a common-base transistor amplifier stage. We are interested mainly in the operating voltages and the phase relationship of the input and output signals.

Two separate batteries supply the proper bias at the junctions of the PNP-type transistor in figure

18. The grounded base is common to the input and output circuits, which is the reason for the designation "common base."

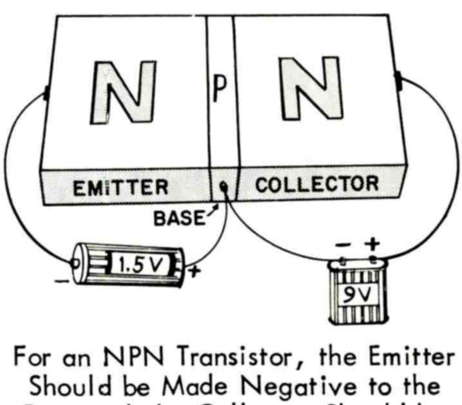
The emitter is forward biased by the 1.5 volt battery, the current at the emitter junction being limited to the correct value by emitter resistor RE. The emitter is 0.2 volt positive with respect to the base, and for a PNP transistor this constitutes a typical forward bias.

The collector junction is biased in the expected reverse direction by the 6-volt battery. As a result of emitter-collector current through the collector resistor (RC), there is a 4-volt drop across the resistor and the collector is two volts negative with respect to the base. These are the established DC values for the transistor before a signal is applied. Let's see what happens when a signal reaches the emitter.

A positive input signal to the emitter makes the emitter more positive with respect to the base and increases (1) the forward bias, (2) the collector current, and (3) the drop across the collector resistor. As a result of this increased drop, the collector becomes less negative with respect to ground. This is effectively the same as going positive and, at the output, the swing is from zero to some positive voltage. From this action we see that the output voltage swings in the same direction as the input signal; there is no phase change between input and output.

During the negative half-cycle of the input voltage at figure 18, the opposite action takes place. The emitter becomes less positive, decreasing the forward bias. The collector current decreases and so does the voltage across the collector resistor. This means that the collector is now more negative with respect to ground and the output swings in the negative direction. Thus, on both the positive and the negative alternation, the output has the same phase as the input.

The fact that the common-base circuit of figure 18 causes no phase change in the output and input signals is not a function of the type of transistor used; instead, it is a function of the nature of the circuit itself. An NPN transistor used as an amplifier in a common-base circuit will also produce signals at the output which are in phase with those of the input.

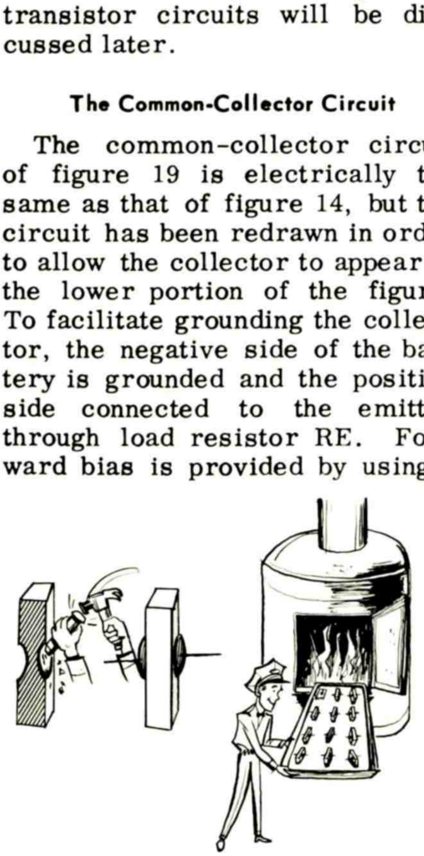


For an NPN Transistor, the Emitter Should be Made Negative to the Base and the Collector Should be Positive.

The values chosen for the analysis of figure 18 are the same as those of figures 16 and 17. This was done for convenience and does not necessarily imply that the gain of this circuit will be the same as that of the common-emitter circuit. Comparative gains of transistor circuits will be discussed later.

The Common-Collector Circuit

The common-collector circuit of figure 19 is electrically the same as that of figure 14, but the circuit has been redrawn in order to allow the collector to appear at the lower portion of the figure. To facilitate grounding the collector, the negative side of the battery is grounded and the positive side connected to the emitter through load resistor RE. Forward bias is provided by using a voltage divider (R1 and R2) across the battery and connecting the base at the midpoint. The resistance values are chosen so that the emitter is 0.2 volt positive with respect to the base.



In Actual Transistor Construction, Wells are Made in the Sides of the Base. Emitter and Collector Materials are Next Placed in the Wells. The Entire Assembly is Then Heated to a Specific Temperature for a Predetermined Length of Time.

The positive half-cycle of the input signal swings the base more positive, lowering the forward bias and causing the emitter current to decrease. With less current through the emitter resistor, the voltage drop is also less and the emitter becomes more positive with respect to ground--this is a positive swing of the output voltage.

During the negative portion of the input voltage swing, the base is driven negative (less positive), increasing (1) the forward bias of the base-emitter junction, (2) the emitter current through the emitter resistor, and (3) the voltage drop across the resistor. The emitter is now less positive with respect to ground and the output swings negative.

During each alternation of the input signal, the output voltage changes in the same direction. This means that the input and output are in phase; there is no phase reversal.[2]

Summary

In this lesson we have learned about the general construction of the grown junction and alloy type transistors. Transistors may be constructed either "PNP" or "NPN," the letters indicating the material used for the emitter, base, and collector, respectively.

2. See TM11-690, pages 42-51.

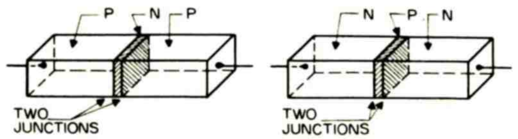
Transistors usually have their emitter-base junction biased in the forward direction and their collector-base junction reverse biased. Forward emitter bias produces a certain amount of emitter current, most of which appears as emitter-collector current and very little of which becomes emitter-base current. The reverse bias of the collector junction prevents any appreciable amount of collector-base current.

The ability of the transistor to amplify depends to a considerable extent upon the ability of a small variation in the base current to cause a larger change in the collector current. (More will be said about this in the next lesson.)

In this lesson we also discussed the standard symbols used for transistors, and we learned how the transistor resembles the triode vacuum tube in some respects. We found that there are three main transistor circuits, namely, the common emitter, the common collector, and the common base. The latter two, common base and common collector, provide an output waveform which has the same phase as the input. The common-emitter arrangement, however, causes a phase reversal (180°) between the output and the input.

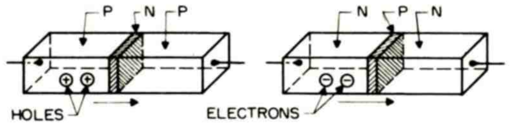
STUDENT NOTES

STUDENT NOTES



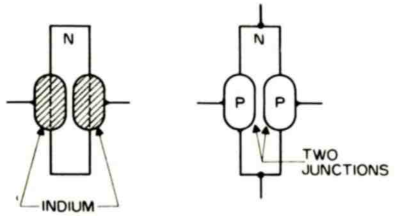
PNP TRANSISTOR (A) NPN TRANSISTOR (B)

FIGURE 1



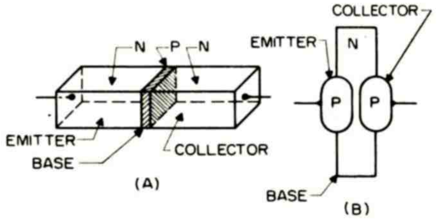
PNP TRANSISTOR (A) NPN TRANSISTOR (B)

FIGURE 2



ALLOY JUNCTION TRANSISTOR

FIGURE 3



THE THREE ELEMENTS

FIGURE 4

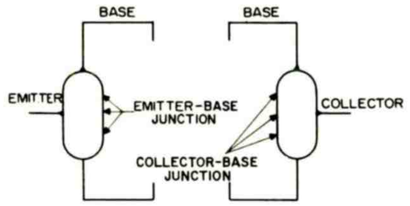
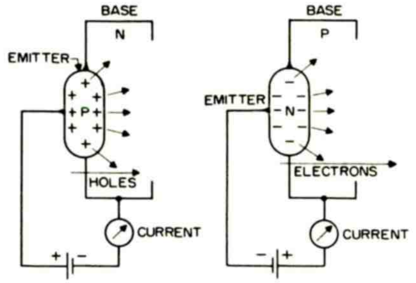
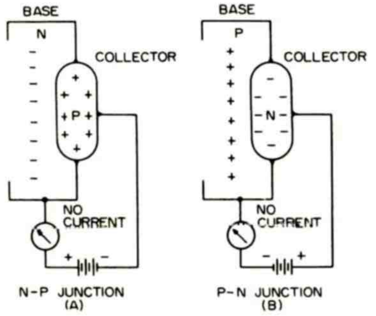


FIGURE 5



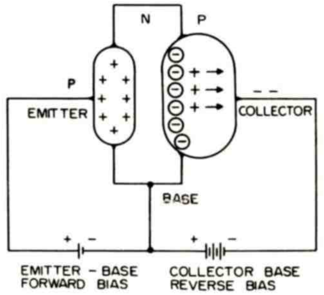
FORWARD EMITTER-BASE BIAS

FIGURE 6



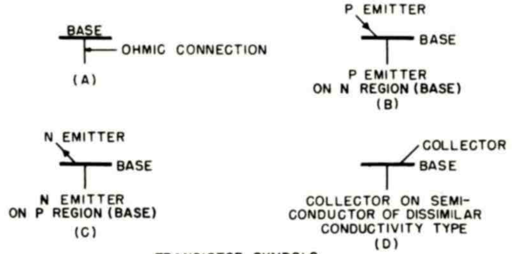
REVERSE COLLECTOR-BASE BIAS

FIGURE 7



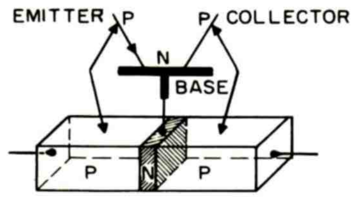
NORMAL TRANSISTOR BIAS

FIGURE 8

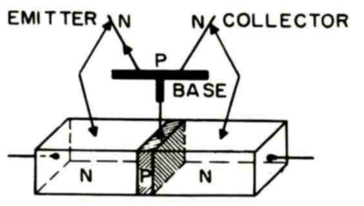


TRANSISTOR SYMBOLS

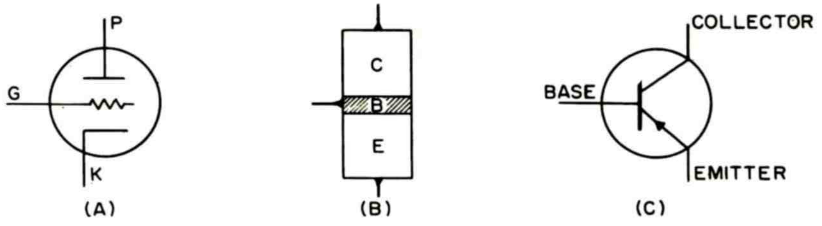
FIGURE 9



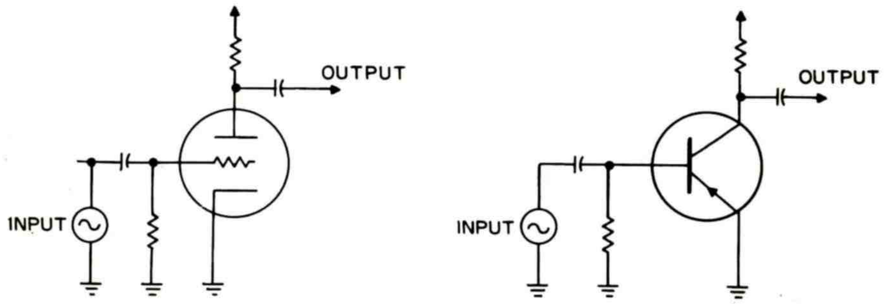
SYMBOL PNP TRANSISTOR
FIGURE 10A



SYMBOL NPN TRANSISTOR
FIGURE 10B



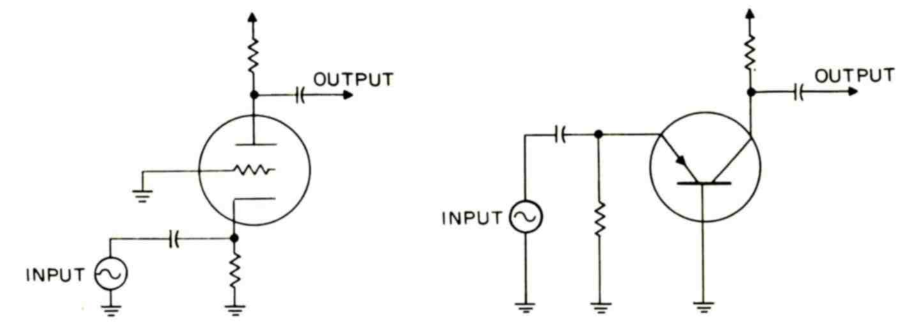
VACUUM TUBE–TRANSISTOR ELEMENTS
FIGURE 11



GROUNDED CATHODE

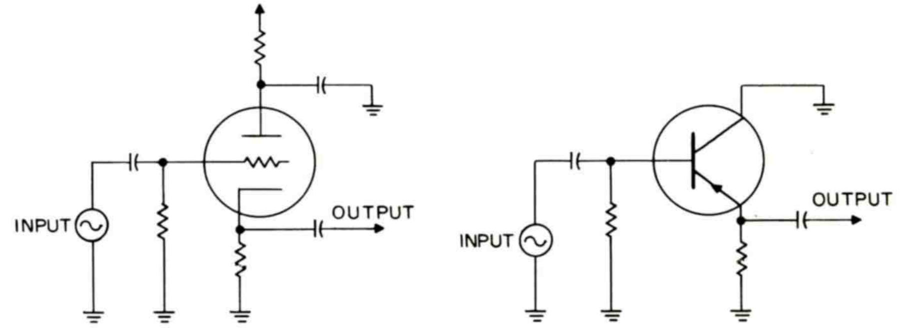
COMMON EMITTER

FIGURE 12



GROUNDED GRID — COMMON BASE

FIGURE 13



CATHODE FOLLOWER — COMMON COLLECTOR

FIGURE 14

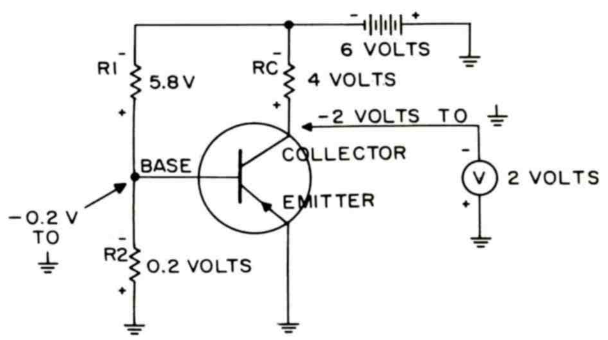
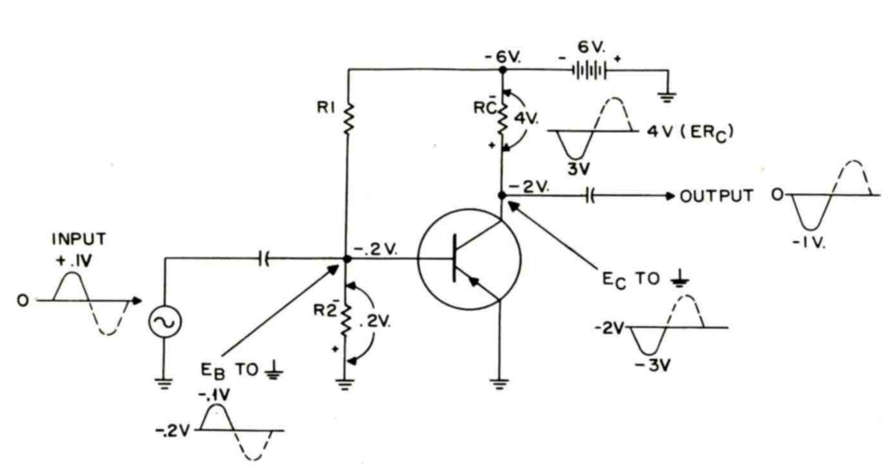


FIGURE 15

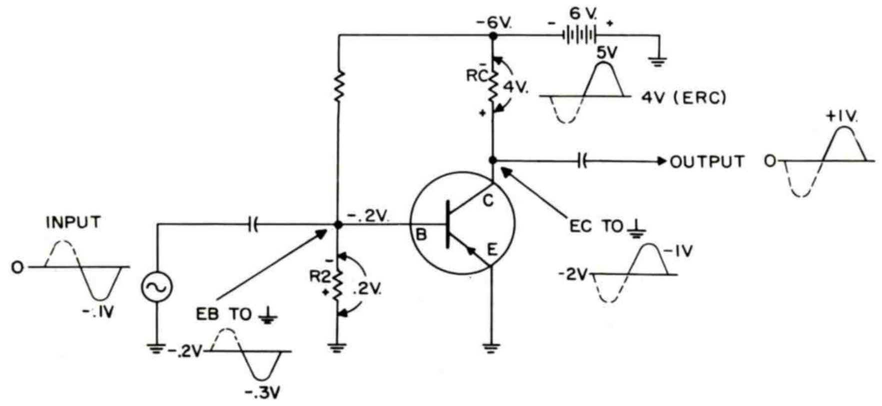


ACTION

1. FORWARD BIAS DECREASES
2. COLLECTOR I "
3. VOLTAGE ERC "
4. COLLECTOR SWINGS MORE NEGATIVE
5. OUTPUT SWINGS NEGATIVE

PHASE REVERSAL–
COMMON EMITTER CIRCUIT
(POSITIVE ALTERNATION)

FIGURE 16

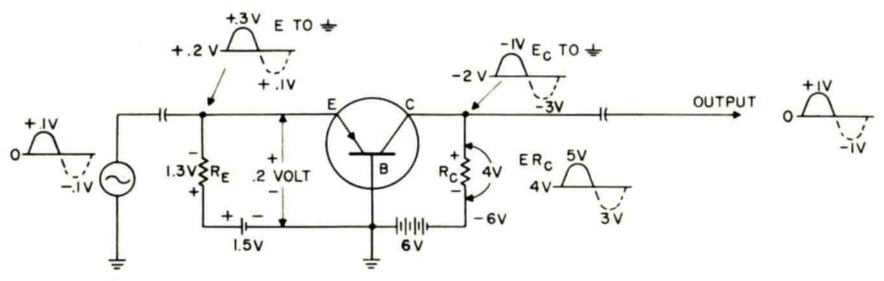


ACTION

1. FORWARD BIAS INCREASE
2. COLLECTOR I "
3. VOLTAGE ERC "
4. COLLECTOR TO ⏚ SWINGS LESS NEGATIVE
5. OUTPUT SWINGS POSITIVE

PHASE REVERSAL OF
COMMON EMITTER CIRCUIT
(NEGATIVE ALTERNATION)

FIGURE 17

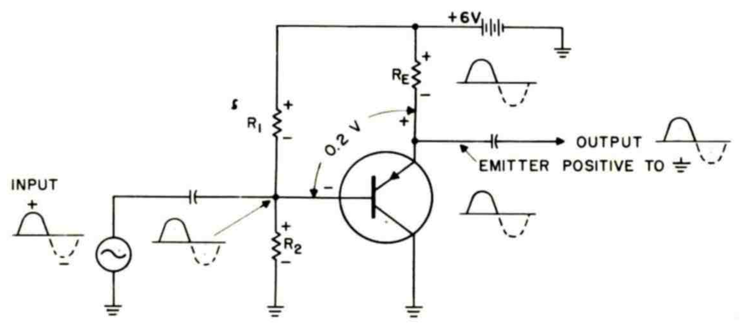


ACTION

"+" ALTERNATION	"–" ALTERNATION
1. FORWARD BIAS INCR.	FORWARD BIAS DEC.
2. COLLECTOR I INCR.	COLLECTOR I DEC.
3. E OF R_C INCR.	E OF R_C DEC.
4. E_C TO ⏚ GOES +	E_C TO ⏚ GOES –
5. OUTPUT SWINGS +	OUTPUT SWINGS –

COMMON BASE CIRCUIT
PHASE RELATIONSHIP

FIGURE 18



"+" ALTERNATION	"–" ALTERNATION
1. FORWARD BIAS ↓	FORWARD BIAS ↑
2. EMITTER-CURRENT ↓	I_E ↑
3. E R_E ↓	E R_E ↑
4. E_E TO ⏚ GOES +	E_E TO ⏚ GOES NEG.
5. OUTPUT GOES +	OUTPUT GOES NEG.

PHASE RELATIONSHIPS
COMMON COLLECTOR

FIGURE 19

national

MOTOROLA

RADIO COMMUNICATIONS

service

A TWO-WAY RADIO COMMUNICATIONS TRAINING PROGRAM

LESSON SA-4
TRANSISTORS

Transistor Amplifiers

MOTOROLA TRAINING INSTITUTE

A TWO-WAY RADIO COMMUNICATIONS TRAINING PROGRAM

LESSON SA-4
TRANSISTORS

Transistor Amplifiers

—one of a series of lessons on two-way FM communications—

MOTOROLA TRAINING INSTITUTE
4501 W. AUGUSTA BLVD., CHICAGO 51, ILLINOIS
APPROVED BY THE STATE OF ILLINOIS
DEPT. OF REGISTRATION AND EDUCATION

PREFACE

This is one lesson of a complete Motorola Home-Study Course which presents to the Service Technician both the principles of operation and the maintenance of two-way FM radio systems The program covers mobile, portable and base station equipment, including the latest transistorized units.

TRANSISTOR AMPLIFIERS

LESSON SA-4

TABLE OF CONTENTS

NOTICE

Diagrams and figures referenced in text are "fold-outs" in back of each lesson, for use while studying. The Examinations are also there.

Industrial "Dispatcher" radiophone is designed specifically for use on materials handling vehicles such as this fork truck. Radio control of such trucks greatly increases storage and warehousing efficiency.

TRANSISTOR AMPLIFIERS--TYPICAL VALUES

Lesson SA-4

Introduction

In this lesson we shall discuss the transistor amplifier, being especially concerned with the ratio of the collector current to the emitter current or to the base current. In addition to the current gain of the transistor, we are interested in the output resistance or impedance compared with that of the input, for in many circuits this ratio accounts for the stage gain. We shall also see various methods of inter-stage coupling for transistor amplifiers.

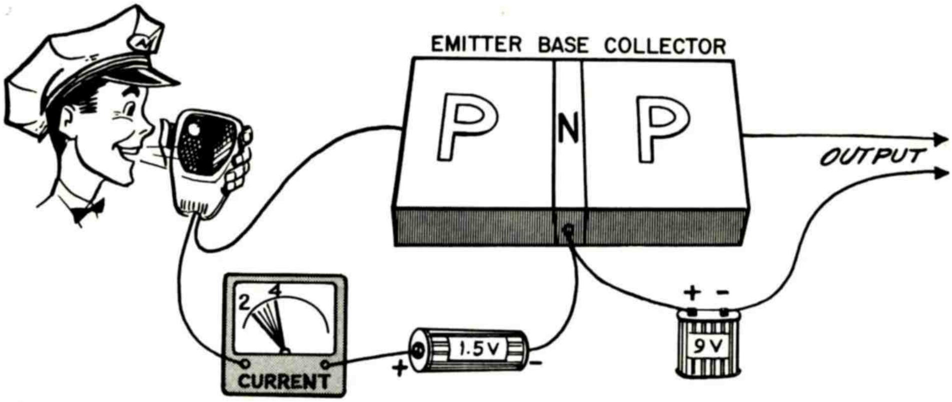
One means of classifying transistors is according to their power capabilities, and in this lesson we shall deal only with low-power devices. (Higher power units, such as those which drive speakers, will be discussed in a later assignment.) These are the things which we are about to study in this assignment. We shall start with the currents in the transistor.

Transistor Currents

Unlike the vacuum tube--which operates on the principle that a small variation of voltage at its input causes a considerable change in plate current--the transistor is not basically concerned with the input voltage. Instead, transistor operation depends upon a changing current at its input junction, for the current at this junction controls the collector current.

When we speak of the transistor input, then, we refer to current variations at the emitter-base junction; although the input may be expressed in terms of the externally applied voltage, we should think of the change of current taking place across the junction.

For the average low-power transistor, 98 per cent or more of the emitter current becomes collector current. This means that only 1 or 2 per cent of the emitter current is left for base current. Figure 1 shows these currents. Here we find a PNP transistor in a common-base configuration, with separate batteries biasing the emitter and collector. The emitter supply is typically low, 1.5 volts. The emitter resistor and the emitter-base section of the transistor are in series and connected across the 1.5 volt battery.



In Transistor Operation, the Current Changes are More Important than the Input Voltages: These Current Changes Control the Output Signal.

Most of this battery voltage appears across the resistor and the balance is the voltage drop across the emitter-base transistor terminals--the 0.2 volt is representative of many low-power units.

The amount of current established at the emitter junction is much more important than the 0.2 voltage drop across the emitter and base terminals. The emitter resistor is chosen to allow the desired amount of current, and in figure 1 this is 1 ma. With normal collector bias, the emitter current divides into 0.98 ma of collector current and 0.02 ma of base current.

One important factor in the operation of the transistor and the amount of collector current should be recognized at this time. Once the collector bias is sufficient that the emitter carriers released into the base are captured by the collector, the value of collector voltage has little effect on the amount of collector current; increasing the collector voltage does not noticeably increase the collector current. Collector current depends primarily upon and is controlled by the emitter current.

Alpha (h_{FB} and h_{fb})

For the common-base circuit of figure 1, the current gain--which we call "alpha" and refer to as "α", the Greek symbol for alpha --is the ratio of the collector current to the emitter current. (This applies only to the condition where the collector load impedance is zero.) For the values of figure 1, then, alpha is equal to 0.98 divided by 1, or 0.98. In the common-base circuit, the input (emitter) current is always greater than the output (collector) current, which means that the value of alpha will always be less than unity (1).

The term alpha was originally established to express the current relationships of the common-base circuit, and there may be some confusion as to whether this applies to DC currents or to AC currents. Thus, in order to differentiate between them, we now use the expressions "h_{FB}" and "h_{fb}," respectively, the "B" indicating a common base circuit and the capital or small letters referring either to DC or to AC.

The DC current gain h_{FB} also indicates the approximate current gain (of the common-base circuit) for large signal inputs. While the values assumed above are for the DC considerations of figure I, the same results are evidenced if we consider an input signal of sufficient amplitude to swing the emitter current between zero and 1 ma. The corresponding change of collector current will be from zero to 0.98 ma. Here we have a change of 1 ma at the input causing a change of 0.98 ma in the output; the ratio of the change in output current to the change of input current is .98.

The current gain (h_{fb}) for small signal inputs will be nearly the same as the DC current ratio so long as the stage operates on the linear or straight portion of its characteristic curve. If the small signal operates over some other portion of the curve, however, the gain will vary with the steepness or "slope" of the curve.

From our discussion this far it may seem impossible to secure any amplification or gain from the transistor, for the output current does not vary as much as the input current. As we shall soon see, however, the input resistance (or impedance) is low while that of the output is considerably higher. This provides voltage amplification and power gain in the stage. Before discussing this further, however, it is well that we first look at the current relationships of other transistor circuits.

Beta (h_{FE} and h_{fe})

Figure 2 shows the circuit of a common-emitter amplifier, and we have assumed the same values used in figure 1: the emitter current is 1 ma, the base current is 0.02 ma, and the collector current is 0.98 ma. Before we discuss the current gain of this circuit, however, we shall study the biasing arrangement, for only one battery is used to provide both the forward emitter bias and the reverse collector bias.

Disregarding the meter in the emitter circuit, the emitter is connected to the positive side of the battery and is the most positive point in the circuit--all other points will be negative (less positive) by comparison. Forward emitter bias is secured by connecting the base return to the midpoint of R1 and R2. The bias voltage is then the voltage across R1 minus the voltage drop across base resistor RB. We will assume that the net voltage between the base and emitter is 0.2 volt, the same as for figure 1.

Reverse collector bias is provided by returning the collector load resistor (RC) to the negative side of the battery, which is "ground" in figure 2. Although both the base and the collector are negative with respect to the emitter, the collector is negative (less positive) compared to the base and hence is reverse biased.

For the common-emitter circuit, the input current includes just the base current--not the entire emitter current. Thus, the input current is very small compared to the output or collector current, and the current gain is the ratio of the collector current to the base current. For the common-emitter circuit of figure 2, the current gain, which was originally called Beta (β), is 0.98 divided by 0.02, or 49. This is the DC current gain, so we use the designation h_{FE}, the capital "FE" indicating DC currents and the "E" indicating a common-emitter circuit. In addition, this rating is for the condition of a short-circuit load at the output.

From the values of figure 2, then, we may deduce that a change of but .02 ma at the input (from 0 to 0.02 ma) can cause a change of 0.98 ma at the output, a gain of 49. This is the current gain of the common-emitter circuit for large signal inputs. The current gain for small signals is designated h_{fe}.

Current gains for this circuit range from low values of around 20 to values in excess of 200.

Alpha-Beta Conversions

There are definite relationships between the alpha (α) and beta (β) current ratings of a transistor which allow a direct conversion from one to the other. The conversion formulas are as follows:

$$(1) \quad \beta \quad (h_{FE}) = \frac{\alpha}{1 - \alpha}$$

$$(2) \quad \alpha \quad (h_{FB}) = \frac{\beta}{1 + \beta}$$

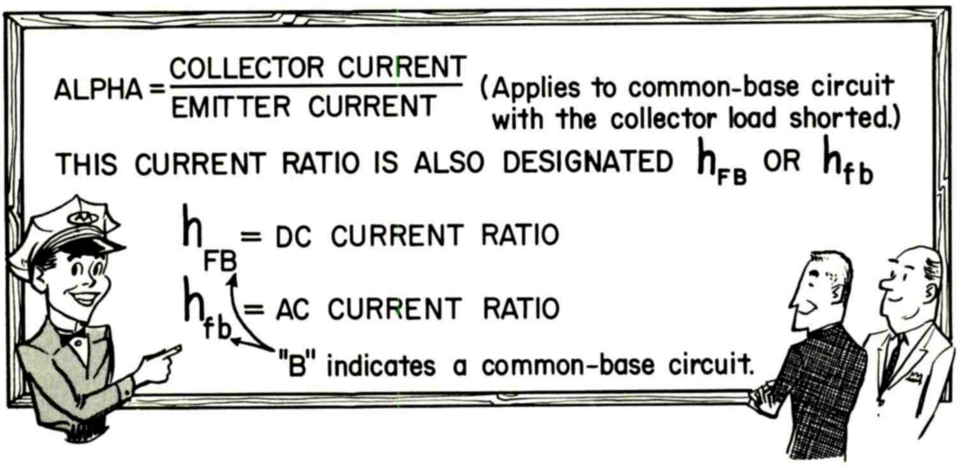
Let's take the values of figures 1 and 2 and see if these conversion formulas apply. From figure 1 we have an alpha of 0.98. Applying this value in formula (1) we have:

$$\beta = \frac{\alpha}{1 - \alpha} = \frac{.98}{1 - .98} = \frac{.98}{.02} = 49$$

Using this value of beta (49), we convert to alpha by using formula (2):

$$\alpha = \frac{\beta}{1 + \beta} = \frac{49}{1 + 49} = \frac{49}{50} = .98$$

From the above, we see that these formulas may be used to convert from a given value of alpha or beta to the other with relative ease.



Alpha and "h_{FB}" or "h_{fb}" Ratings Refer to the Common-Base Circuit With the Collector Load Shorted.

Common-Collector Currents

The preceding discussions about transistor currents (including alpha and beta ratings) are concerned with common-emitter and common-base circuits. Nothing has been said so far about the currents of the common-collector circuit. This arrangement is seen in figure 3.

In the common-collector circuit, although the collector is common to both the input and the output, as far as the current gain is concerned we are interested in the base and emitter currents; they are the input and output currents, respectively. Thus, the current gain is the ratio of the emitter current to the base current. Using the values of figures 1 and 2 for figure **3**, we have a ratio of 1 ma to 0.02 ma, a current gain of 50.

At first consideration, with a high current gain it appears that the gain realized in this common-collector circuit is the highest of all three circuits. On the contrary, there are other considerations which enter into the picture to cause the lowest power gain and a voltage loss for the common-collector arrangement. The circuit has some characteristics, however, which makes it very useful and advantageous in certain specific applications. We shall study the circuit in greater detail later.

In foregoing discussions we have mentioned the resistances or impedances of the various transistor circuits and the fact that transistor amplifier gain depends upon a higher impedance in the output than present at the input. We are now ready to look further into this matter, beginning with the input.

Input Resistance-Impedance

We often hear the term "input resistance" used in connection with both vacuum-tube and transistor amplifiers. While resistance normally refers to the opposition offered to DC current, it is used more freely here to indicate the impedance or opposition to AC. Strictly speaking, however, resistance should be reserved for DC opposition and in the following discussion we shall follow this idea and reserve the term impedance (Z) for the AC opposition.

"Input Impedance," then, is the opposition to AC current encountered by a signal applied to the input of some device. This impedance is not always constant, but varies with frequency and other factors. As an example of input impedance, inspect figure 4. Here an input signal is applied to a transistor amplifier, and the amplifier offers a certain amount of opposition (Z) to AC current.

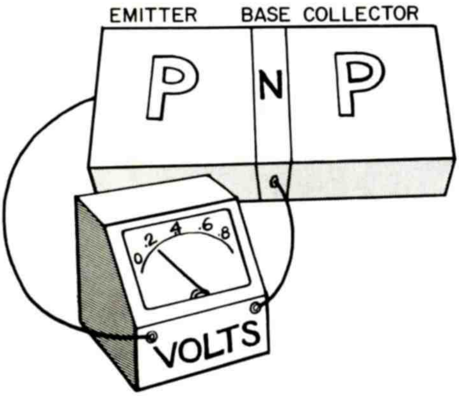
The amount of impedance may be determined if the input signal voltage (e_{in}) and the current (i_{in}) are known. This impedance may then be calculated by applying Ohm's Law for AC circuits, in which impedance (Z) is substituted for "R," the DC opposition. The formula now becomes: $Z = e_{in} \div i_{in}$. The small letters are used here to indicate signal current and voltage.

In figure 5 we see a more detailed circuit showing the input impedance of the transistor amplifier. This is a common-base arrangement, and for simplicity the biasing arrangement has been omitted.

There are two parallel paths for the applied signal--through emitter resistor RE and through the emitter-base section of the transistor. The resistance (and impedance) of the emitter resistor is usually considerably greater than the impedance of the transistor, so, being in parallel, it does not greatly change the net impedance. The total impedance in this instance is determined almost entirely by the transistor.

The emitter-base impedance for this particular circuit is usually in the vicinity of 200 ohms or less, meaning that the input impedance for the common-base circuit is very small. This low value of input impedance is different from the high input resistance we have become accustomed to for the vacuum tube, where the grid is biased to prevent grid current.

The above mentioned value of 200 ohms or less is typical for low-frequency applications where the reactances (opposition to AC current) of the various circuit capacitances are sufficiently high that they do not affect the impedance. At high frequencies, however, these reactances must also be taken into consideration, for they further decrease the input impedance. Transistor circuit behavior, such as feedback from the



The Average Forward Bias at the Emitter-Base Terminals of a Transistor is About 0.2 Volt.

output to the input, also alters the effective impedance at the input, and again the effect varies with the frequency and the circuit arrangement.

Output Impedance

AC currents in the complete output circuit of an amplifier encounter two separate impedances. Represented in figure 6, these are: (1) the impedance internal to the device (the transistor in this case) and (2) the external or "load" impedance. If we are to avoid confusion, it is important to differentiate between these two impedances. Thus, we will refer to the internal impedance as the "output" impedance, and to the external impedance as the "load."

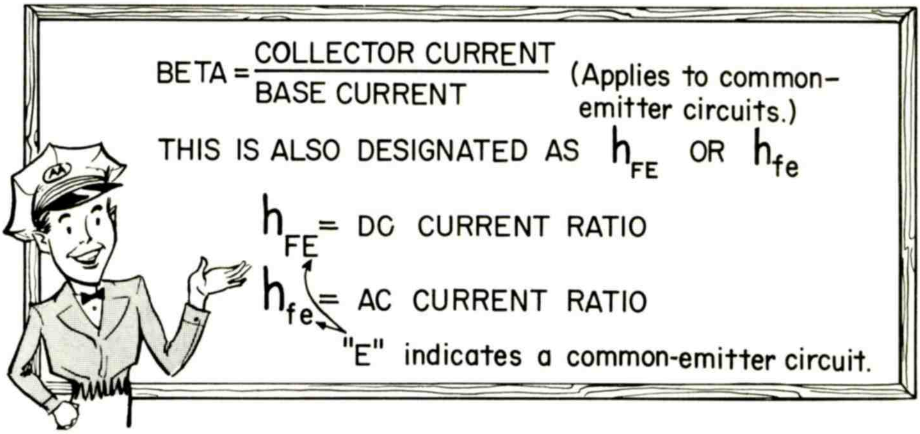
The internal impedance cannot be isolated to just one separate factor internal to the transistor. Instead, it depends upon many factors such as the ratio of the collector current to the collector voltage, the internal feedback of the unit, and the current gain of the device.

Similarly, the load impedance cannot be limited to the resistor, coil, or tuned circuit which may be in the collector DC current path. Instead, anything connected to the output of the amplifier, such as the input circuit of the following stage, becomes part of the output circuit and alters the load impedance.

In figure 6 the amplifier terminates into a "load." For the final stage of a receiver, this load is the speaker. In many instances the load is the input circuit to another amplifier. Regardless of the nature of this load, its presence must be taken into consideration in determining the load impedance of the amplifier.

Figure 7 shows a typical output arrangement of a transistor amplifier which terminates into the input of another amplifier. The collector or output circuit has three paths for the signal: (1) collector resistor RC, (2) emitter resistor RE, and (3) the emitter-base section of the next stage. (The coupling capacitor is chosen to have negligible opposition to currents at the signal frequency.)

The net impedance offered by those three parallel paths is the load impedance of the amplifier



Beta and "h_{FB}" or "h_{fb}" Ratings are Determined with the Collector Load Shorted.

stage. For the transistor amplifier, it is usual practice to match the load impedance to the output impedance, for this produces maximum gain. For the common-base arrangement we have been considering, 50,000 to 100,000 ohms is a typical output impedance.

Impedance Gain

The fact that the transistor usually presents a low input impedance and a high output impedance accounts for its consideration as a TRANSfer-resISTOR. If it were not for this impedance transformation, the transistor might not be desirable as an amplifier.

For the common-base circuit, a small signal current through a low impedance is transferred into a similar signal current at the output, but here the current is established in a high impedance. The "gain" of this circuit is determined almost entirely by the impedance ratio or gain.

Before discussing voltage amplification and power gain in transistor circuits, however, we shall look at the typical impedances of the various circuits. At this point in our discussion we will consider only the typical impedances for low-frequency applications, such as those used for audio amplification.

Common-Base Circuit Impedances

The common-base circuit--see figure 8--offers the lowest input impedance and the highest output impedance of all the various transistor configurations. We have already discussed typical values for the common base circuit in the preceding paragraphs, finding that the input impedance is likely to be below 200 ohms. In fact, it would not be unusual for this impedance to be below 50 ohms at higher frequencies.

The output impedance often may be as high as 100,000 ohms or more, but it is not always possible to match this high output impedance in the load. Merely to insert a high impedance component in the collector circuit is not enough. The impedance of the remainder of the output circuit (the input to the next stage, etc.) must be taken into consideration. A further discussion of this involves coupling methods and devices and more will be said about these things a little later in this lesson.

The ratio of the output impedance to the input impedance is the highest for the common-base circuit. This means that the impedance gain of the circuit is the highest of the three transistor arrangements. Impedance gains as large as 1000 or more are common.

Common-Emitter Circuit Impedances

The input impedance of the common-emitter circuit is not as low as that of the common-base circuit and its output impedance is not as high as that of the common-base arrangement. As indicated in figure 9, a typical input impedance ranges from 1000 to 5000 ohms and the output impedance is likely to be somewhere between 10K and 50K ohms.

The impedance ratio or gain of the common-emitter circuit is usually around 10, which means that this circuit, which has the highest gain of all the various circuits, does not depend upon the impedance gain alone for its ability to amplify. We may recall from our preceding discussion that a current gain is also realized by this circuit.

Common-Collector Circuit Impedances

The impedance condition for the common-collector circuit (figure 10) is different from that of the common-base and common-emitter circuits--there is no impedance gain from the input to the output. Instead, the input impedance is higher than the output impedance.

It is not practical to suggest typical impedance values or ranges of the common collector circuit, for the input impedance is determined to a large extent by the load impedance. We can, however, express a relationship between the input and output impedance: depending upon the current gain of the transistor, the input impedance will usually be somewhere between 20 times to 100 times the output impedance. Thus for an output impedance of 1000 ohms, the input impedance will probably be between 20K and 100K ohms. Again, we are speaking of low-frequency applications.

While the common-collector circuit has an impedance loss from its input to its output, it has a relatively high value of current gain which compensates to a large extent for the impedance loss and makes the circuit very desirable and practical for certain applications, such as impedance transformation.

Amplification and Gain--Common Base Circuit

We have already spoken of the current gain within the common-base circuit--the gain being h_{FB}, the ratio of the collector current to the emitter current. In addition, we found that this circuit possesses a high impedance gain. These two factors account for the voltage amplification and power gain of the common-base transistor amplifier.

The amount of voltage amplification is determined by the ratio of the output signal voltage to the input signal voltage and, by applying Ohm's Law to both the input and output circuits, we can readily determine these voltages from the currents and impedances.

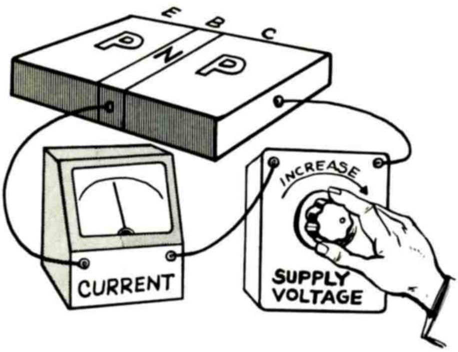
Referring to figure 11, with an input signal current of 0.1 ma and an input impedance of 50 ohms, the input voltage is 0.005 volt; the output voltage is calculated to be 4.9 volts (using the output current and impedance). The ratio of the output voltage to the input voltage is 980. This value corresponds closely to the impedance gain of 1000.

If the current gain (alpha) were unity, the voltage amplification would be equal to the impedance ratio. The same value of voltage amplification (980) results if we use formula (2) in Figure 11, and multiply the h_{FB} by the impedance gain.

The power gain of the stage is the true indication of the worth of the circuit as an amplifier, and the power gain is the ratio of the output signal power to the input signal power. We can determine the power gain of the common-base circuit of figure 11 from the values that are already known--the procedure is given in figure 12. In fact, once the three values of voltage, current and impedance are known, any of the formulas for determining power may be used.

From figure 12 we find that the power gain is 960, indicating that the output power is 960 times greater than the power at the input. This value is also nearly the same as the impedance gain; as the value of h_{FB} approaches unity the power gain approximates the impedance gain. In addition to finding the power gain from known values of output and input power, we may determine the power gain from alpha and the impedance gain--the formula is given in figure 12. (This assumes the load impedance is small compared to the output impedance.)

The gain of the stage as specified in decibels is conveniently determined from the power gain. A power gain of 1000 is a 30-db



Once Collector Current has been Established in the Transistor, Increasing the Collector Voltage has Little Effect Upon the Collector Current.

gain, so a gain of 960 is slightly less than 30 db. The actual calculation (using "logs" or a chart) establishes the gain at 29.8 db.

The db gain of the stage is determined from the power gain rather than from the voltage ratio or amplification. The only time it is permissible to determine the db rating from the voltage is when the input and output voltages appear across the same value of impedance. This is not true of the transistor circuits of figures 11 or 12.

Amplification and Gain--Common Emitter Circuit

Figure 13 shows the basic arrangement of a common-emitter amplifier, and we have assumed the same current values as for figures 11 and 12. The impedance gain of 10 is typical for this configuration.

The voltage amplification is determined in the same manner as was done for the common-base circuit. Two methods of determining the amplification are given in figure 13: (1) the ratio of the output and input voltages, and (2) the current gain multiplied by the impedance gain. The results (490) are the same in both calculations.

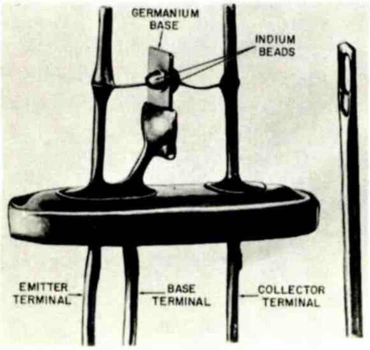
The power gain of the common-emitter circuit is illustrated in figure 14. Calculations for the individual powers of the input and output circuits are impractical in that they involve very small decimal values. It is much more convenient to determine the power gain from the known current and impedance ratios, and the answer will be the same. As shown, the power gain is approximately 24,000, and this is considerably greater than the power gain of the common-base circuit. This is a 44 db gain, a value possible to realize in practical circuitry.

Since the power gain of a circuit is the true indication of the amplifier's worth, the common emitter circuit is the most often used. Only where their characteristics are more suitable for the needs of a particular stage is it advantageous to use other circuits.

Amplification and Gain – Common Collector Circuit

We have already seen that the common-collector circuit is similar in its operation and characteristics to the cathode-follower vacuum-tube circuit. Continuing with this comparison, the common collector would be called an "emitter follower." There is no voltage amplification and the power gain of the circuit is the lowest of all three transistor arrangements. The current gain of the circuit is the highest, being the ratio of the emitter (output) current to the base (input) current. The current gain is slightly higher than beta (h_{fe}).

Referring to the common-collector circuit of figure 15, with an emitter current of 0.1 ma and a base current of .002 ma, the current gain is 50. With this high value of current gain we might anticipate a large voltage amplification and power gain, but there is an impedance loss rather than a gain, with the result that there is no voltage amplification and little power gain--the stage is not very desirable as an amplifier. Instead, this circuit is usually employed as an impedance-matching device.



Here We See the Actual Construction of a Low-Power, Low-Frequency Transistor. The Actual Size May be Judged by the Size of the Needle at the Right.

The output impedance is determined to a great extent by the source impedance and the current gain. In practical circuitry we find that the input impedance is between 20 and 100 times the load impedance.

The voltage ratio of the output to the input (the amplification) is found by the now familiar method of multiplying the current gain by the impedance gain. Regardless of how large the current gain may be, the impedance ratio always changes accordingly and the amplification is always less than 1.

The power gain is also determined from the current and impedance ratios. In the figure we find that a power gain of 45 has been realized, and this is relatively low compared to the power gains of the common-base and common-emitter circuits. If transistors having higher current gains are used, the power gain will also be higher. Typical values of power gain range from 20 to 200 (13 to 23 db).[1]

Coupling Transistor Stages

Whether we are concerned with vacuum tube or transistor amplifiers, the coupling between stages or at the input and output presents a problem. The procedures and

1. See Basic Theory and Application of Transistors (TM11-690) pages 52-84 and pages 102-111.

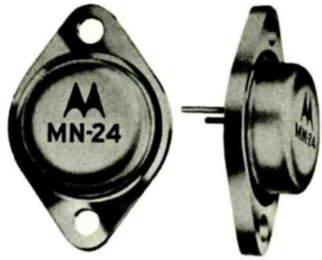
considerations associated with vacuum-tube amplifiers also apply to transistor circuits. Compared to vacuum tube circuitry, however, transistor input and output impedances usually have a greater variation and hence require closer attention.

Among the more perplexing problems encountered in transistor circuitry which are not as noticeable with vacuum tubes are the interaction between the input and output circuits and the effect of the impedance of one circuit upon the impedance of the other. As an example, as the output load impedance increases the input impedance decreases and vice versa. This effect is hardly noticeable with vacuum tubes, for changes of plate load impedance do not notably change the effective grid impedance.

The most common methods of coupling transistor stages are transformer coupling and RC coupling. We shall discuss each of these separately, beginning with transformer coupling.

Transformer Coupling

Maximum gain within one stage or several stages of amplification is made possible by the impedance-matching transformer. By adjusting the turns ratio, the output impedance of one stage is matched to the input impedance of the next (or to some other load). Unless a match is effected, the over-all gain will be sacrificed.



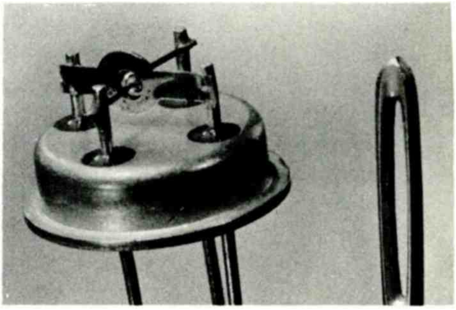
This Power Transistor is Considerably Larger Than the Low-Power Transistors Discussed in this Lesson.

Transformers, unfortunately, have several disadvantages. They are heavy and space consuming, which is not conducive to their use in light, compact equipment. In addition, transformers which are small enough to be practical for such equipment are expensive. Transformers are also subject to hum pickup and core saturation.

Transformers for transistor circuits are designed in much the same manner as those for vacuum-tube circuits. The turns ratio is determined by the desired impedances of the primary and secondary, and each winding depends upon the power requirements and the desired frequency response.

Figure 16 shows a simple circuit of a common-emitter amplifier stage having transformer coupling at both its input and its output. The biasing method for this circuit is interesting--one battery is used for both emitter and collector bias. The positive side of the battery is grounded and is thus connected directly to the grounded emitter.

A voltage divider composed of R1 and R2 provides the desired forward emitter bias, with the voltage across R2 being the voltage at the emitter and base. The collector is connected to the negative side of the battery through a transformer winding and, with negligible DC voltage drop across the windings, the voltage across R1 is the reverse collector bias.



This Photo Shows the Typical Construction of Medium-Low Power Audio Transistors.

The input transformer (figure 16) serves as an impedance-matching device between a high-impedance source (connected to the primary of the transformer) and a low-impedance load (the input circuit of the amplifier). Because of this impedance match, maximum signal power reaches the input circuit.

The fact that the primary has a greater number of turns than the secondary means that the low-impedance load of the secondary actually looks like a high impedance to the primary. (The reflected impedance to the primary is determined by the square of the turns ratio. A transformer having a 5 to 1 turns ratio has an impedance ratio of 25 to 1, and a 1000 ohm load at the secondary looks like a 25000 ohm load in the primary.)

It may appear that the lower secondary voltage (due to the step-down ratio of the transformer) is less desirable than a higher voltage such as that of the primary. This is not the case. We must remember that the transistor is a current operated device, and the fewer turns in the secondary is capable of delivering higher currents to the low-impedance input circuit--assuming that the impedances are matched--than can be delivered by a higher voltage secondary. By matching the impedances, then, maximum power is available at the input circuit of the amplifier. The signal currents in the base circuit--through the emitter-base junction--cause appreciable changes in collector current.

At the output of the stage we have the same problem encountered :- the input--a high impedance is desirable for the collector circuit, but the load (the input of the following stage) is a low impedance. Again the impedance-matching transformer is the answer. The primary of the output transformer has a large number of turns and a high impedance; the secondary has fewer turns and a low impedance.

The turns ratio is controlled so that the load impedance at the secondary reflects the desired impedance into the collector circuit. Thus, the effective load in the collector circuit depends directly upon the impedance of the load connected to the secondary.

The circuit of figure 16 is by no means the final arrangement which might be found in equipment. There are other factors such as feedback and neutralization which often require additional circuitry, and, in most transistor circuits, some provision is made to minimize the effects of temperature changes within the transistor. These things will be discussed in detail as we progress with our study of transistor circuits and operation. Right now we are ready to continue with coupling methods.

RC Coupling

While transformer coupling is advantageous to use in audio circuits where large signal currents and powers are present, or where tuned circuits are necessary, the RC coupled amplifier finds many applications where compactness, light weight and economy are the important factors. R-C coupling is particularly adaptable to low-level audio stages, where the hum pickup by transformers is very detrimental.

Figure 17 gives the basic circuit components of RC coupling between stages. The coupling components are the collector resistor (RC), the coupling capacitor (CC) and the base resistor (R2). These components correspond to the plate load resistor, the coupling capacitor and the grid resistor, respectively, in RC-coupled vacuum-tube stages.

Resistor R1 forms a voltage divider with R2 to provide forward bias to the emitter junction of transistor Q2. The output voltage of the first stage is coupled to the base of the second stage by the coupling capacitor. The reactance (AC resistance) of this unit must be small compared with the impedance of the associated resistors, and with a low-impedance input to the second stage, the reactance of the capacitor will be extremely low--much lower than we are accustomed to find in vacuum tube-circuits. In fact, in order to provide a low reactance for this capacitor at low audio frequencies, it is necessary to use an electrolytic or tantalum type. Due to the low supply voltage, a unit having a low voltage rating will suffice.

Another difference between the coupling capacitor of figure 17 and that of the vacuum-tube circuit is in the tolerable leakage current. The slight leakage of electrolytics does not normally have any great effect upon the operation of transistor stages, although the same leakage in vacuum-tube circuits may produce a substantial change in the operation and damage some of the circuit components.

Unlike transformer coupling, RC coupling does not provide an impedance match between stages. The input of the second stage determines to a large extent the impedance presented to the output section of the preceding stage. As a result, the RC-coupled amplifier provides less power gain; their gain varies with the degree of matching between the desired impedance at the output of one stage and the input impedance of the next stage.

Figure 18 compares the gains that may be realized with two stages of RC coupling, using different configurations and various values of input and output impedances. The indicated gains are for transistors having the characteristics shown at the top of the figure. The configurations of the stages are abbreviated CB, CC and CE, referring to common base, common collector and common emitter, respectively.

The two columns at the left show source and load impedances. Stages in the upper group have the same input and output impedances; those in the middle group have input impedances which are lower than the output impedances; those in the last group have output impedances which are lower than the input impedance.

The importance of matching the transistor impedances can be seen by the gains for the two-common collector stages, (1) where the input is low and the output high, and (2) where the input is high and the output is low. With a 100-ohm source and 100K-ohm load, the (CC) gain is -24 db, indicating a considerable loss. A 100K-ohm source and a 100-ohm load, however, result in a gain of 33.5 db. The difference in gain is thus 57.5 db, a power ratio of nearly 1,000,000 to 1.

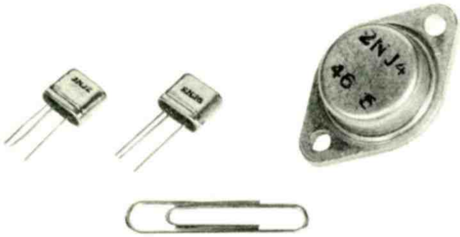
Although the double common-emitter arrangement yields maximum gain in most instances, there are certain conditions where some of the other configurations yield comparable results, often with a reduction of distortion.

Other Coupling Methods

In addition to transformer and RC coupling, we occasionally find impedance-coupled and direct-coupled stages. Let's discuss briefly each of these.

Impedance coupling is very similar to resistance coupling, the only difference is that one of the two resistors used for RC coupling is replaced by a coil or a tuned circuit. In figure 19A, we find a coil (1) in the collector circuit of Q1. This coil presents an impedance to AC currents at the signal frequency. The big difference between this and RC coupling is that the coil offers a high impedance to AC but at the same time its DC voltage drop is very small.

Direct coupling is shown in figure 20. Only one resistor, common to both the collector and base,



Here We See the Comparative Size of Low and High Power Transistors.

is required. The collector of Q1 is connected directly to the base of Q2, so these two points are at the same DC potential. The circuit has several distinct advantages. First, there are a minimum number of parts in the coupling circuit, resulting in savings of both space and money. Second, where the DC components of the signal must be preserved (or amplified) it is still present at the output of Q2. (One particular application is the DC restorer-amplifier circuit of TV receivers.)

There is one great disadvantage, however, which prevents greater use of direct coupling. All transistors have a certain amount of DC instability with changes of temperature. This problem is multiplied by successive stages of direct coupling, with the result that a large amount of feedback must be used to bring about satisfactory stability. This feedback limits the gain which may be realized in each stage.[2]

Summary

In this lesson we studied the various currents and impedances in the three transistor circuits, the common base, the common emitter and the common collector. We found that the amplification and gain provided by each circuit are dependent upon the current gain and the impedance gain, and comparisons were made for the three configurations--they are summarized in figure 21.

The low input impedance and the high output impedance of the common-base circuit give a high impedance gain, but the current gain (h_{FB}) is always less than unity. While the resulting voltage amplification is high, the power gain is only medium. In addition, we learned in a preceding lesson that the circuit does not produce a phase inversion (180^{o} phase shift) of the input and output signal. This circuit is convenient to use between a very low impedance source and a high impedance load.

The common-emitter circuit has only a medium impedance gain, but this coupled with a high current gain (h_{FE}) produces a high voltage amplification and the highest power gain. There is a phase reversal of the input and output signal. This is the most popular circuit for transistor amplifiers.

The common-collector circuit has a higher input impedance than

2. See TM11-690, pages 118-124.

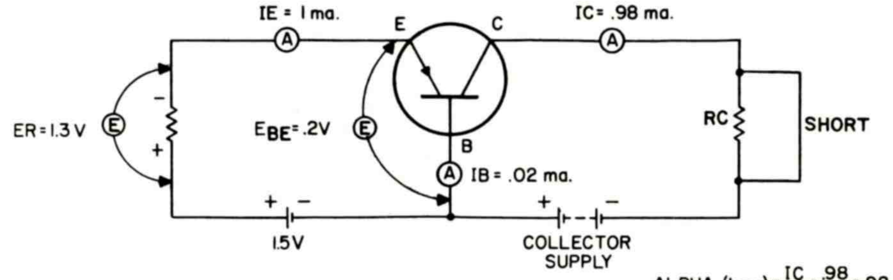
output impedance, resulting in a considerable impedance loss. Although the current gain is high, the voltage amplification is always less than unity and the power gain is the lowest of all three circuits. The output signal has the same phase as the signal input. This circuit is used primarily for impedance-matching purposes, from a high impedance to a low impedance loss.

In this lesson we also learn about the transformer and RC coupling. Transformer coupling is used where impedance matching is important and the signal is large. Tuned transformer coupling is normally found in IF and RF circuits. RC has the advantage of being compact and lightweight; it is used extensively in low-frequency, low-level stages.

STUDENT NOTES

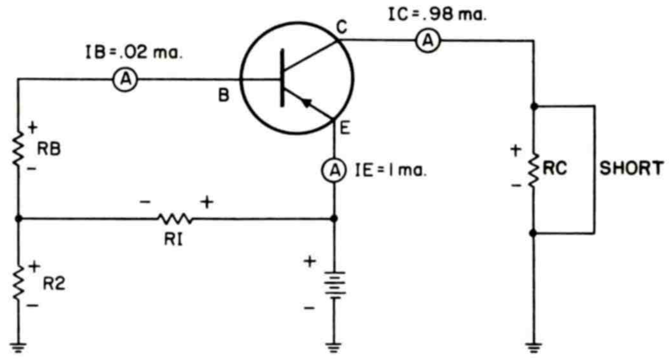
STUDENT NOTES

STUDENT NOTES



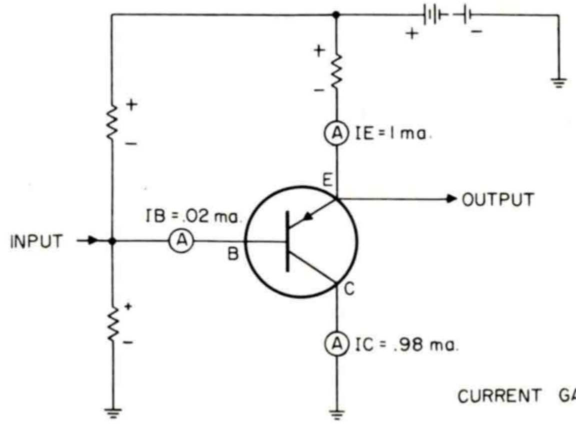
COMMON BASE AMPLIFIER
FIGURE I

ALPHA $(h_{FB}) = \frac{IC}{IE} = \frac{.98}{1} = .98$



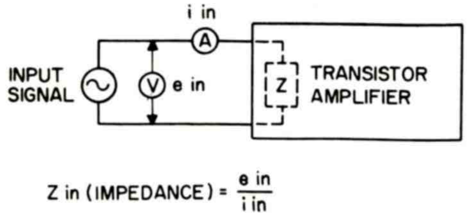
BETA $(h_{FE}) = \frac{IC}{IB} = \frac{.98}{.02} = 49$

COMMON EMITTER AMPLIFIER
FIGURE 2



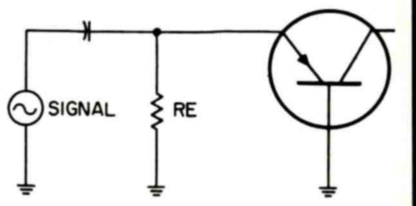
CURRENT GAIN = $\frac{IE}{IB}$

COMMON COLLECTOR
FIGURE 3

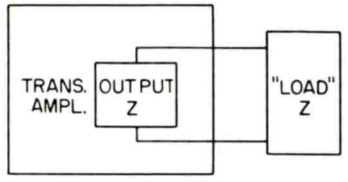


Z in (IMPEDANCE) = $\frac{e\ in}{i\ in}$

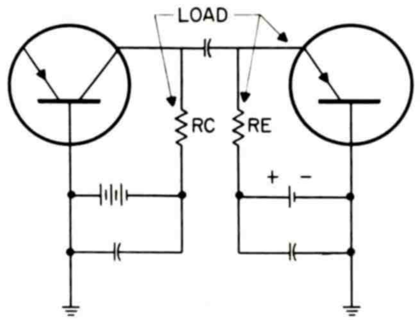
INPUT IMPEDANCE
FIGURE 4



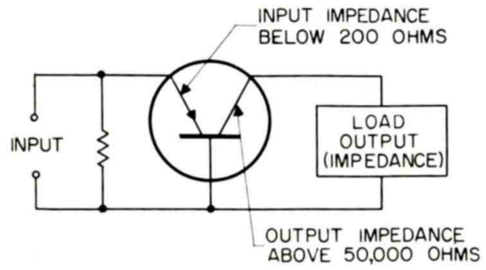
INPUT IMPEDANCE
FIGURE 5



OUTPUT IMPEDANCE
FIGURE 6

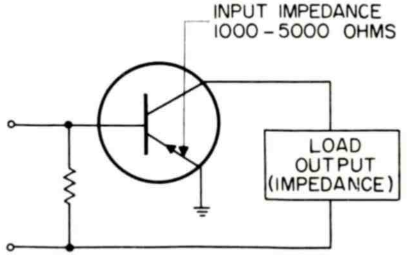


OUTPUT LOAD (IMPEDANCE)
FIGURE 7



IMPEDANCES GAIN: 1000 OR MORE

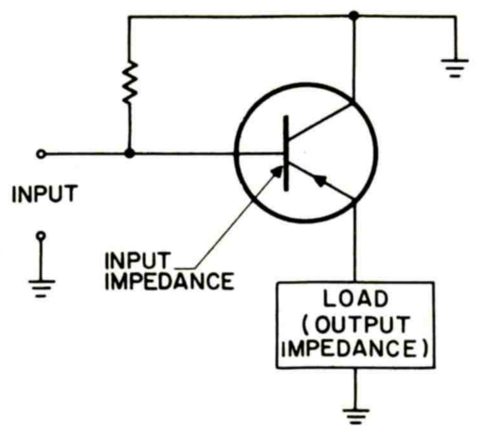
"COMMON BASE" IMPEDANCES
FIGURE 8



LOAD IMPEDANCE 10K-50K OHMS

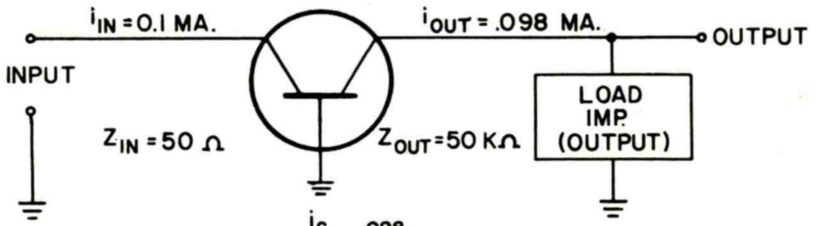
IMPEDANCE GAIN: 10

"COMMON EMITTER" IMPEDANCES
FIGURE 9



INPUT IMPEDANCE 20-100 TIMES THE OUTPUT IMPEDANCE
NO IMPEDANCE GAIN

"COMMON COLLECTOR" IMPEDANCES
FIGURE 10



$$\text{ALPHA} = \frac{i_c}{i_e} = \frac{.098}{.1} = .98$$

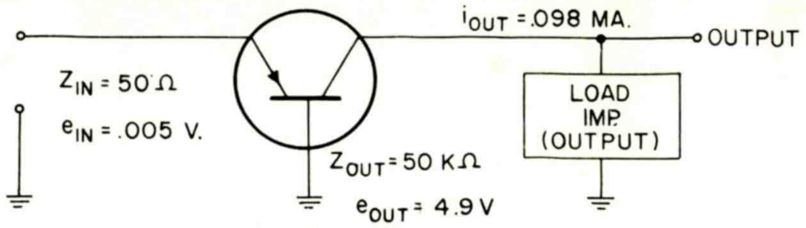
$e_{IN} = i_{IN} \times Z_{IN}$
$= .0001 \times 50$
$= .005$ VOLT

$e_{OUT} = i_{OUT} \times Z_{OUT}$
$= .000098 \times 50{,}000$
$= 4.9$ VOLTS

1. VOLTAGE AMPLIFICATION $= \frac{e_{OUT}}{e_{IN}} = \frac{4.9}{.0005} = 980$

2. VOLTAGE AMPLIFICATION = ALPHA x Z GAIN
= .98 x 1000 = 980

VOLTAGE AMPLIFICATION
COMMON BASE CIRCUIT
FIGURE 11



$$hFB = \frac{i_{OUT}}{i_{IN}} = \frac{.098}{.01} = .98$$

1. POWER GAIN $= \frac{P_{OUT}}{P_{IN}} = \frac{I^2 Z}{I^2 Z}$

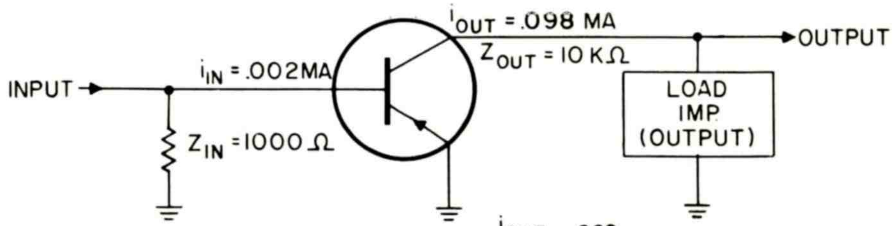
$$= \frac{(.000098)^2 \times 50{,}000}{(.0001)^2 \times 50}$$

$$= 960$$

2. POWER GAIN $= hFB^2 \times$ Z GAIN

$$= .98^2 \times 1000$$
$$= .96 \times 1000$$
$$= 960$$

POWER GAIN
COMMON BASE CIRCUIT
FIGURE 12



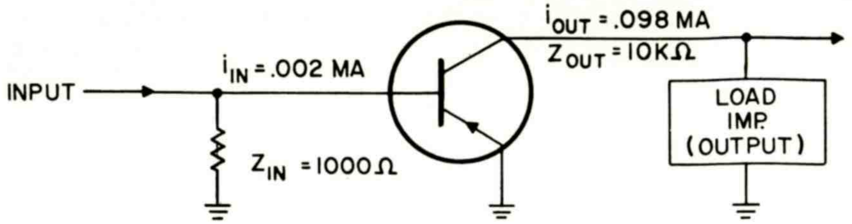
$$\text{BETA (B)} = \frac{i_{OUT}}{i_{IN}} = \frac{.098}{.002} = 49$$

$e_{IN} = i_{IN} \times Z_{IN}$
$= .000002 \times 1000$
$= .002$ VOLT

$e_{OUT} = i_{OUT} \times Z_{OUT}$
$= .000098 \times 10{,}000$
$= .98$ VOLT

1. VOLTAGE AMPLIFICATION $= \frac{.98}{.002} = 490$
2. VOLTAGE AMPLIFICATION = B x Z GAIN
   $= 49 \times 10 = 490$

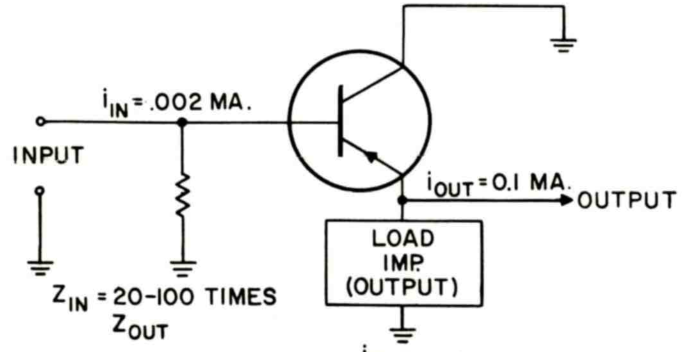
VOLTAGE AMPLIFICATION
COMMON EMITTER AMPLIFIER
FIGURE 13



$$\text{BETA (B)} = \frac{i_{OUT}}{i_{IN}} = \frac{.098}{.002} = 49 \qquad \text{Z GAIN} = \frac{Z_{OUT}}{Z_{IN}} = \frac{10\text{ K}}{1\text{ K}} = 10$$

POWER GAIN $= (B)^2 \times$ Z GAIN
$= (49)^2 \times 10$
$= 24000$
$= 44$ db.

POWER GAIN
COMMON EMITTER AMPLIFIER
FIGURE 14



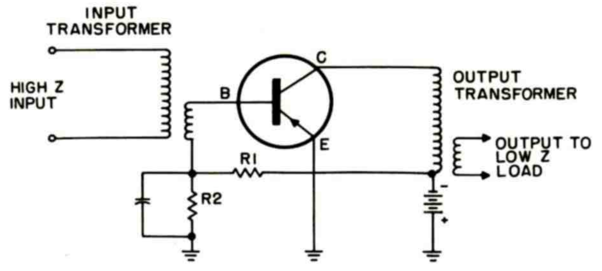
CURRENT GAIN $= \frac{i_{OUT}}{i_{IN}} = \frac{.1}{.002} = 50$

Z GAIN IS THEN LESS THAN $\frac{1}{50}$

VOLTAGE AMPLIFICATION = CURRENT GAIN x Z GAIN
$= 50 \times \frac{1}{55}$
$= .9$

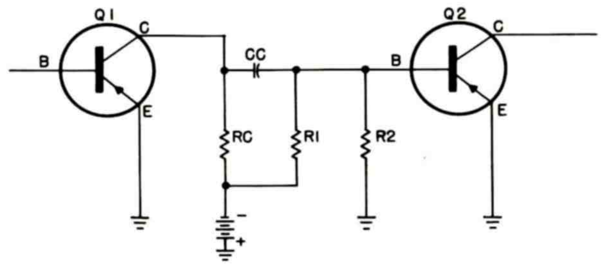
POWER GAIN $= (\text{CURRENT GAIN})^2 \times$ Z GAIN
$= (50)^2 \times \frac{1}{55}$
$= 45$ (16.5 db.)

AMPLIFICATION AND GAIN
COMMON COLLECTOR CIRCUIT
FIGURE 15



TRANSFORMER COUPLING

FIGURE 16



"RC" COUPLING

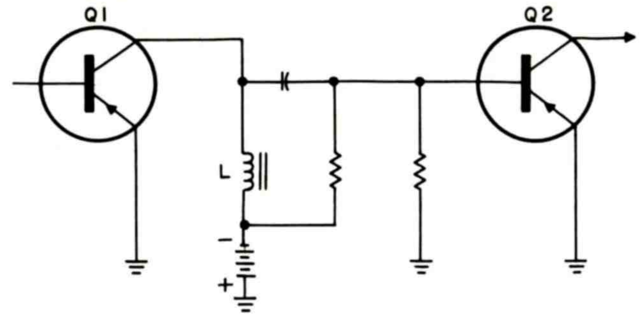
FIGURE 17

TRANSDUCER GAIN OF CASCADED PAIRS OF TRANSISTOR AMPLIFIERS

$r_e = 25\Omega$ $r_b = 600\Omega$ $r_c = 2 \times 10^6 \Omega$ $\alpha = 0.985$

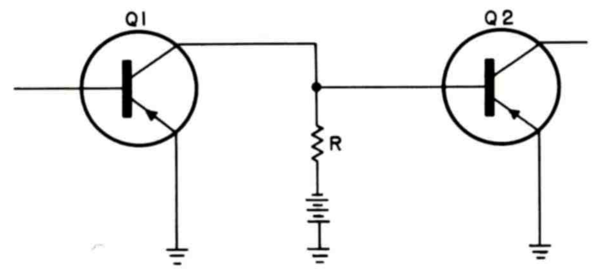
1st STAGE		CE	CB	CC	CE	CB	CE	CC	CC	CB
2nd STAGE		CE	CB	CC	CB	CE	CC	CE	CB	CC
SOURCE	LOAD	POWER GAIN IN DECIBELS								
100	100	51.6	3.2	3.5	14.8	39.7	51.4	15.1	9.0	39.6
1000	1000	71.6	5.6	5.8	32.0	41.9	63.0	35.1	27.5	41.9
10K	10K	74.5	6.0	6.0	40.5	39.8	51.2	54.4	39.0	37.8
100K	100K	66.0	5.4	6.0	42.1	29.5	41.1	62.4	41.8	24.6
100	1000	61.6	13.2	-4.2	24.8	49.7	58.3	25.1	19.1	48.5
100	10K	68.8	23.2	-13.9	32.0	57.0	56.9	35.1	28.7	49.9
100	100K	68.6	32.8	-24.0	44.8	56.9	41.1	41.6	35.8	42.8
100K	100	48.6	-24.0	33.5	12.1	12.2	48.7	40.8	12.0	12.4
10K	100	57.0	-14.0	23.5	20.5	22.2	57.1	34.6	19.1	22.4
1000	100	58.5	-5.5	13.5	22.0	31.9	58.6	25.1	17.5	32.1

FIGURE 18



IMPEDANCE COUPLING

FIGURE 19



DIRECT COUPLING

FIGURE 20

CIRCUIT	CURRENT GAIN	INPUT Z	OUTPUT Z	Z GAIN	VOLTAGE AMPL.	POWER AMPL.	180° PHASE SHIFT
COMMON BASE	LESS THAN 1 (ALPHA)	LOW	HIGH	HIGH	HIGH	MEDIUM	NO
COMMON EMITTER	HIGH (BETA)	MEDIUM LOW	MEDIUM HIGH	MEDIUM	HIGH	HIGH	YES
COMMON COLLECTOR	HIGH	HIGH	LOW	LOSS	NONE	LOW	NO

FIGURE 21

national
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LESSON SA-5
TRANSISTORS

Transistor Bias: DC Circuitry

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A TWO-WAY RADIO COMMUNICATIONS TRAINING PROGRAM

LESSON SA-5
TRANSISTORS

Transistor Bias: DC Circuitry

—one of a series of lessons on two-way FM communications—

MOTOROLA TRAINING INSTITUTE
4501 W. AUGUSTA BLVD., CHICAGO 51, ILLINOIS
APPROVED BY THE STATE OF ILLINOIS
DEPT. OF REGISTRATION AND EDUCATION

PREFACE

This is one lesson of a complete Motorola Home-Study Course which presents to the Service Technician both the principles of operation and the maintenance of two-way FM radio systems. The program covers mobile, portable and base station equipment, including the latest transistorized units.

TRANSISTOR BIAS - DC STABILITY

LESSON SA-5

TABLE OF CONTENTS

NOTICE

Diagrams and figures referenced in text are "fold-outs" in back of each lesson, for use while studying. The Examinations are also there.

By using portable two-way radiophones, inventories and parts checking can be accomplished very efficiently. Waste motions and trips are cut to a minimum.

TRANSISTOR BIAS - DC STABILITY

Lesson SA-5

Introduction

In this lesson we shall discuss the various methods of providing bias for the three transistor circuits, the common emitter, the common base and the common collector. We shall also see the methods of stabilizing transistor operation against variations of temperature; unless some means of limiting the effects of heat is introduced, transistor operation may change drastically with temperature.

Common-Emitter Bias Circuits

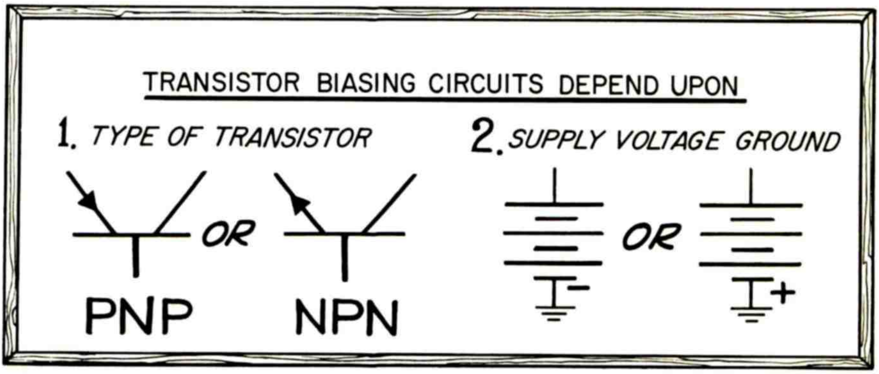
The final bias arrangement of any particular amplifier depends upon (1) the type of transistor--whether it is a PNP or an NPN transistor, and (2) whether the supply voltage to the stage has its positive or its negative terminal grounded.

Figure 1 shows a biasing circuit for a PNP-type transistor used as a common-emitter amplifier. The supply voltage has its positive terminal grounded. This means that the grounded emitter is the most positive point in the circuit. All other circuit terminals will be negative (less positive) by comparison.

Forward emitter bias is established between the emitter and base by means of voltage divider R1 and R2. The polarities of the voltages across these resistors are as marked. The voltage across R2 is the forward biasing voltage, for it is the voltage between the emitter and base. For low-power transistors of the type we have been discussing, 0.2 volt is a typical bias value.

Reverse bias between the collector and base of the PNP transistor is established by making the collector negative with respect to the base. Although both elements are negative to ground, the base is only a few tenths of a volt negative while the collector is several volts negative. (The collector-to-ground voltage is the difference between the supply voltage and the voltage drop across the collector resistor.) For typical supply voltages ranging from 6 to 12 volts, the collector will usually be between 3 and 10 volts negative to the base.

The value of the collector resistor is determined by both the required load impedance and the tolerable DC voltage drop. In many instances the collector load is a tuned circuit or a coil, in



The Biasing Arrangement of the Transistor Circuit Varies With (1) the Common or Grounded Terminal of the Supply and (2) the Type of Transistor.

which case the impedance may be made equal to the output impedance of the stage. At the same time, the DC drop across the coil is small and the collector is more negative than it would be if a resistor were used as the collector load.

Figure 2 shows a variation which might be made in the biasing circuit to accommodate a power supply which has its negative terminal grounded. The negative terminal is now the reference and all other points are considered with respect to ground -- they are so many volts positive.

Voltage divider R1 and R2 again provides the desired emitter-base bias voltage, only now the emitter-base voltage is the difference in the voltages of R1 and RB. The voltages across these resistors are opposing as far as the emitter-base voltage is concerned; the voltage across R1 is normally larger than that across RB, however, with the result that the emitter junction is forward biased.

In figure 1 the emitter is grounded, but in most circuits this is not standard practice. Instead, a resistor is connected between the emitter and ground -- see figure 3. A voltage drop is developed across the emitter resistor as a result of emitter current through it. This voltage drop has a polarity which opposes the bias voltage across R2, and the net emitter-base voltage is the difference in these voltages.

The voltage across R2 is greater than that of RE and the emitter junction is forward biased. The emitter resistor (RE) is usually bypassed. We will see the need for this resistor and its bypass later.

Figure 4 shows another biasing method for a common-emitter circuit when the supply voltage has its positive terminal grounded. The circuit is similar to that of figure 1, only in figure 4 there is no voltage divider in the base biasing circuit.

The emitter is connected to the positive side of the supply through emitter resistor RE. The collector is connected to the negative terminal of the supply through collector resistor RC; the collector-ground voltage is equal to the supply voltage less the amount of voltage drop across the resistor (caused by collector current through the resistor). As a result of this circuit arrangement and its voltages, the base is negative with respect to the emitter, but it is positive as far as the collector is concerned.

In figure 4 the voltage drop across the base resistor is determined by the base current through it. In figure 1, however, the voltage of the corresponding resistor, R1, is due mainly to the resistor being a part of the voltage divider, and the resistor has a low resistance compared to RB of figure 4. In figure 4, the only current through the resistor is the small base current and a higher resistance is needed to produce the required voltage drop.

The voltage across emitter resistor RE again has a polarity which opposes the forward bias. Later we shall see how this resistor stabilizes the operation of the stage for temperature changes. At this time we are interested only in its effect upon the initial bias.

Another bias method for the common-emitter circuit and a supply voltage with a positive ground is given in figure 5. The emitter is connected directly to ground and is the most positive point of the circuit. The collector load resistor (RC) connects to the negative side of the battery and the voltage drop across the resistor makes the collector less negative with respect to ground.

The base is connected to the collector through resistor R1, and the voltage drop across R1, due to base current through it, has the indicated polarity. This makes the collector negative to the base and the collector is reverse biased. The emitter is positive to the base, however, so that the emitter is forward biased.

A resistor is sometimes placed between the base and ground as shown in the figure. Where this occurs, the three resistors form a voltage divider between the negative terminal of the battery and ground. Although this additional resistor does not change the polarity of the voltages, different resistance values are required in order to provide the same voltages.

Common-Base Bias Circuits

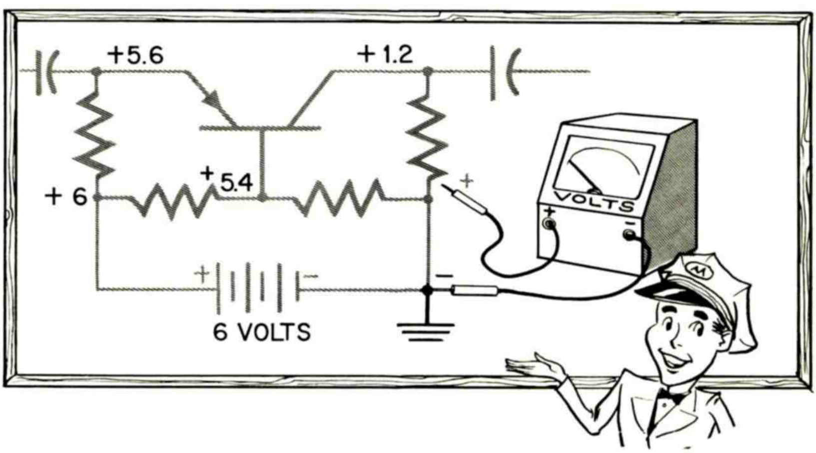
Although the common-emitter circuit provides the greater gain where the impedances are suitable, occasionally a certain stage has characteristics which make it advisable to use the common-base configuration. There are several such instances in Motorola equipment.

Figure 6 shows the bias arrangement of an RF amplifier stage used in a high-band mobile receiver. The supply voltage has a negative ground, which means that the collector may be returned directly to ground through its load, a tuned circuit. For all practical considerations, the collector is at ground DC potential.

Resistors R1 and R2 are the now familiar voltage divider across the supply voltage, with the base returned to the midpoint. The biasing voltage at the emitter-base terminals is the voltage of R1 minus the voltage drop of emitter resistor RE. This resistor serves as the emitter return resistor and as a DC stabilizing resistor. Bypass capacitors are introduced in order to avoid loss of gain due to degeneration.

Figure 7 shows the circuit of a high-frequency (12 mc) IF stage used in a pocket-size, high-band receiver. The positive side of the supply is grounded. The emitter returns to ground through a resistor and the collector is connected directly to the negative side of the battery as far as DC is concerned, for there is no appreciable DC voltage across the coil of the tank circuit.

Resistor R2 of the voltage divider provides for the desired amount of bias voltage between the emitter and base, with the drop across emitter resistor RE opposing the voltage of R2. The voltage across resistor R1 is the reverse collector bias.



With the Negative Side of the Supply Grounded, All the Circuit Terminals are "Positive." To Make Voltage Checks, Ground the Negative Test Lead.

Common-Collector Bias Circuits

The biasing methods for common-collector circuits are similar to those of the preceding figures. Figures 8 and 9 show several variations, depending upon the nature of the source voltage.

In figure 8 the supply voltage is "negative" by virtue of the positive terminal of the battery being grounded. The collector is grounded as far as AC is concerned, and this is realized by the capacitor between collector and ground. As far as DC and bias are concerned, however, the collector is above ground, for it is connected directly to the negative terminal of the battery.

Resistors R1 and R2 are the voltage divider, with the emitter-base voltage being equal to the difference in the voltages of R2 and RE. The voltage across R1 is the collector reverse bias.

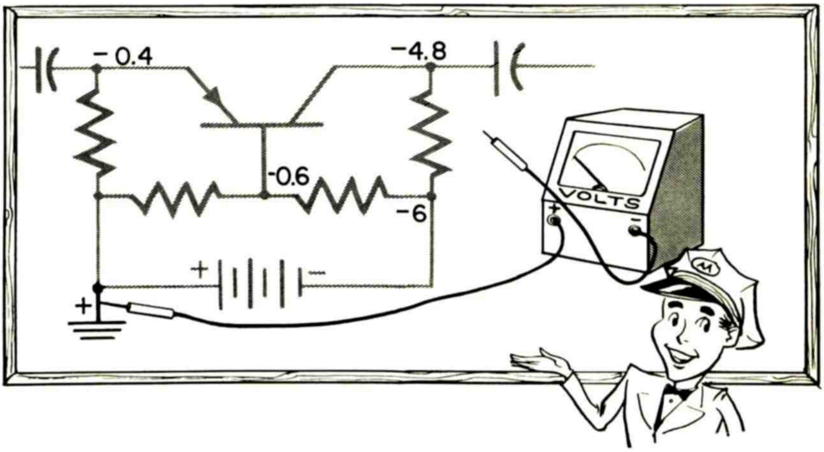
Figure 9 shows a method of biasing the common-collector circuit when the supply voltage has a negative ground. The collector is now connected directly to ground and the emitter returns to the positive side of the supply through the load, RE. Voltage divider resistors R1 and R2 provide the required voltage to the base circuit, with the final emitter-base voltage being equal to the voltage of R1 minus the voltages of RB and RE.

Temperature and Transistor Stability

There are two effects of temperature taking place within the transistor which are detrimental to its operation. First, as the temperature increases, both its power handling ability and its ability to amplify decrease. In fact, if the transistor becomes too hot it is likely to be permanently damaged. The second undesirable effect of transistor temperature is the normal change of DC currents through the transistor with changes of temperature: as the temperature increases the currents also increase.

At this time we will not concern ourselves with the fact that extreme temperatures may damage the transistor, for the low-power transistors we are discussing are not likely to develop sufficient internal heat to cause damage when used in their typical "RC" circuits. Their temperature does increase some as a result of the currents through the junctions, however, and this heat causes an increase of current. Thus, it is essential to introduce some protection or compensation in the circuit which counteracts and limits any current change.

Without going into details of how it happens, we can readily observe on meters that the currents through a transistor increase with an increase in transistor temperature--



Where the Positive Side of the Supply is Grounded, All the Circuit Terminals are "Negative." Ground the Positive Test Lead of the Meter for Voltage Measurements.

see figure 10. With a given forward bias for the emitter and a reverse bias at the collector, the meters record a specific value of emitter and collector current. Without some means of compensation, if the temperature of the transistor increases, the currents also increase.

When we consider that the stage is operating as an amplifier and that it is essential to maintain certain values of DC current for proper operation, we can readily visualize that any major change in the circuit currents can change the characteristics of the amplifier. This is particularly true of transistor amplifiers.

Something must be done to stabilize the DC currents of the stage for changes of temperature. This may be accomplished in several ways, but the most common methods seem to be (1) a series-connected resistor in the emitter circuit and (2) a resistor placed between the collector and base. We will now see the operation of each of these arrangements.[1]

Emitter Stabilizing Resistor

We have already seen the resistor in the emitter circuit and found that the voltage across this resistor opposes the bias voltage to the emitter junction. It is this action which tends to stabilize the DC operation of the stage.

Figure 11 shows a very simple circuit in which one battery is used for bias. The emitter-base forward bias is the voltage across R1, less the voltage across RE.

1. See Basic Theory and Application of Transistors (TM11-690), pages 85-86.

Depending upon the transistor, the bias voltage and the value of the resistors, a certain amount of DC current is established at the emitter junction. We are now ready to see what happens when the currents through the transistor increase due to an increase of transistor temperature.

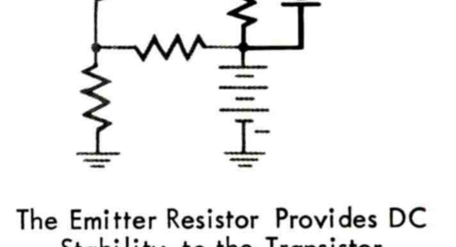
As the emitter current increases, due to an increase of transistor temperature, the voltage across the emitter resistor also increases. An increase of voltage across RE means that the emitter becomes more negative; a negative-going emitter means that there is a decrease in the forward bias voltage, and the current must decrease.

Thus, the increase of voltage across the emitter resistor causes a reduction in current, with the final result that the initial increase due to the temperature rise has been minimized. The net change of current is small--so small, in fact, as to have no appreciable effect upon the operation of the stage.

The emitter resistor in the circuit of figure 11 is a self-biasing type of resistor in which the changes of current through the resistor produce an opposing change in the forward bias. This is almost identical in effect with the bias voltage developed across the self-biasing resistor in the cathode circuit of a vacuum tube amplifier.

We must keep in mind that the changes we have been talking about so far in figure 11 are DC changes which occur over a period of time--they are not the changes due to an applied signal. Thus, the emitter resistor provides protection from undesirable changes of operation due to temperature changes of the transistor.

In addition to this protection from changes in operation due to temperature changes, the emitter resistor also maintains a more constant operation as the transistor ages; for any long-term variations in the DC currents, regardless of their origin, the resistor provides a compensating voltage which minimizes such changes. Thus, the resistor is also beneficial in maintaining more stable operation if a transistor having slightly different current characteristics is substituted for the original transistor.



The Emitter Resistor Provides DC Stability to the Transistor Amplifier; the Bypass Avoids Degeneration Due to the Resistor.

The emitter resistor is incorporated in many amplifier circuits, although in most cases it is necessary to use a large bypass capacitor in parallel with the resistor in order to avoid degeneration and loss of gain in the amplifier.

Figures 12 and 13 show why the unbypassed emitter resistor is degenerative as far as the applied signal and stage amplification is concerned. That is, it produces changes of voltage which oppose the normal changes of current at the emitter junction, thereby reducing the amount of change (signal variations) in the output circuit.

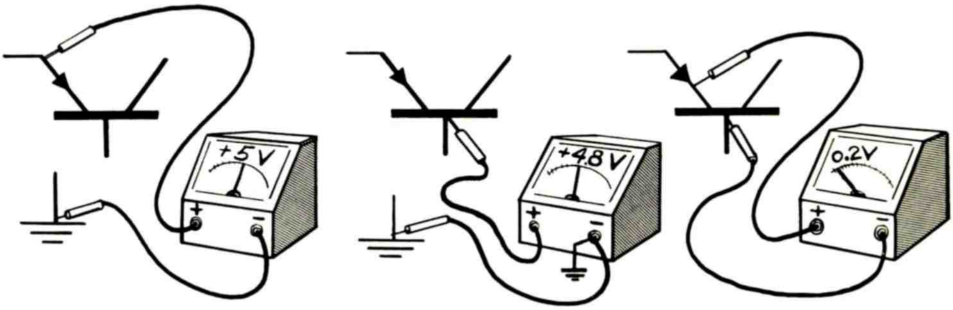
Figure 12 shows the action when the negative portion of the signal is applied to the base of a PNP transistor. The base is driven negative by the signal, increasing the forward bias and current at the emitter junction.

An increase in emitter current also causes an increase in the voltage across the emitter resistor. This means that the emitter swings in a negative direction and reduces the forward bias. This action tends to cause a decrease in the emitter current, but what actually happens is that it opposes the increase taking place as a result of the negative signal applied to the base.

The over-all effect is that the emitter current does not increase as much as it would if the emitter resistor were omitted. With less change of emitter current, there is less current change in the collector circuit, lowering the overall "gain" of the stage.

Figure 13 shows the same effect taking place during the positive half of the signal. That is, the change of voltage across the emitter resistor opposes the change initiated by the signal.

With the base going positive, the forward bias of the emitter junction is reduced and the emitter

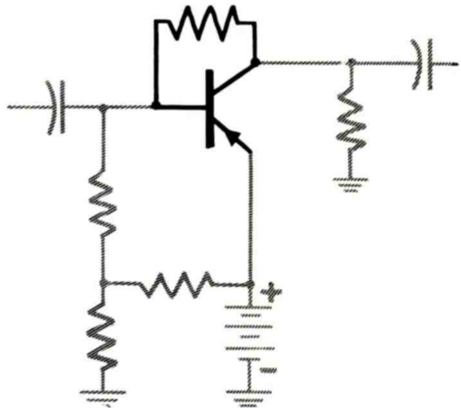


To Determine the Forward Emitter Bias, Measure the Separate Voltages at the Emitter and Base, Both with Respect to Ground. The Difference in the Readings is the Forward Bias. This is Usually More Accurate than a Reading Secured Directly Between the Emitter and Base.

current decreases. This lowers the emitter resistor voltage and the emitter becomes less negative--in effect, it swings positive. A positive going emitter means an increase of emitter current. Of course, the current does not increase, but the original decrease, initiated by the applied signal, is counteracted and becomes a smaller decrease.

The degenerative effect of the changing emitter resistor voltage may be avoided by using a large bypass capacitor across the resistor--see figure 14. This capacitor, assuming it to be sufficiently large to prevent any changes of voltage across the resistor at the signal frequency, maintains a constant voltage at the emitter with respect to ground and thereby prevents the degeneration. Now, the only change at the emitter junction is caused by the applied signal; the stage has been restored to full amplification.

In order for the emitter bypass capacitor to be effective, it must have a reactance which is one-tenth or less the internal resistance of the emitter junction, and this must be at the lowest frequency involved. For an audio amplifier, where both the applied frequency and the emitter resistance are low, this bypass capacitor is usually 50 mfd or larger. This means that an electrolytic (often a tantalum type) is required--fortunately a low-voltage unit will suffice.



The Collector-Base Resistor Gives Good DC Stabilization, But It Also Introduces Degeneration.

Although the resistor is bypassed and its voltage does not change or vary with the signal frequency, this does not have any effect upon the DC stabilization ability of the resistor. Gradual changes of current, taking place over a period of time with changes of temperature, will still cause a change of voltage across the emitter resistor and thereby stabilize the circuit. Thus, while the bypass prevents changes of voltage at signal frequencies, it does not affect those changes taking place over a longer period of time.

Collector-Base Stabilizing Resistor

Figure 15 shows another practical method of providing DC stability in an amplifier. Without the collector-base resistor of figure 15, normal changes of DC current, taking place as a result of temperature changes, will alter the operation of the stage.

The collector-base stabilizing resistor is somewhat similar in its operation to the emitter resistor we have just studied. The base-emitter voltage is determined by the voltage drops across collector resistor RC and stabilizing resistor RB. (The resistor between the base and ground is sometimes omitted, but the operation remains the same.)

As the voltage drops across either or both resistors increase, the base becomes less negative, or, in effect, it swings positive. Conversely, reduced current through either of these resistors causes an increase in the negative voltage of the base with respect to ground, which is an increase in bias. We can now see how this stabilizes the circuit.

Looking at figure 15, assume that the transistor temperature increases and initiates an increase in the emitter-collector current. This increases the voltage drop across the collector resistor and makes the base less negative, which, in effect, is a change in the positive direction. With the base less negative, the forward bias of the emitter-base junction is reduced and lowers the conduction of the transistor. This opposes the original increase in the transistor currents so that the net change is a minimum.

The opposite effect takes place for reductions in transistor temperature. The reduced current and the voltage of the collector resistor makes the base swing negative, thereby increasing the forward bias and opposing the decrease.

Unfortunately, the stabilizing effect of the collector-base resistor of figure 14 also introduces degeneration of the applied signal. When the collector current increases or decreases due to the applied signal, the changing voltage at the base (as a result of the changing voltage drop across the collector resistor) opposes the initial change of current. This means that the gain is lower than that which could be realized without this resistor.

Also unfortunate is the fact that the stabilizing resistor between the collector and base cannot be bypassed as was done for the emitter stabilizing resistor. A bypass capacitor parallel with the resistor would introduce a short between the input and output circuits.[2]

This concludes our discussion about transistor bias and DC stabilization. We will see how these principles are used in practical audio and higher frequency applications in the next two lessons.

2. See TM11-690, pages 87-91.

STUDENT NOTES

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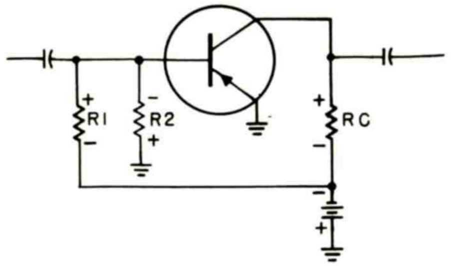
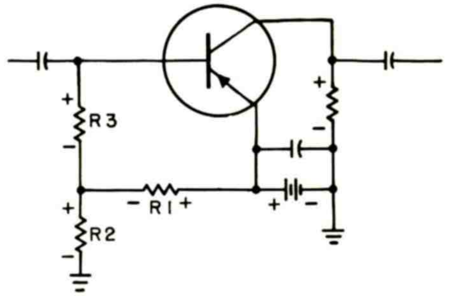


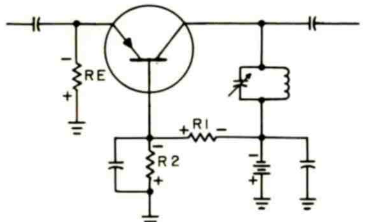
COMMON-EMITTER BIAS CIRCUIT
FOR "POSITIVE GROUND" SUPPLY

FIGURE 1



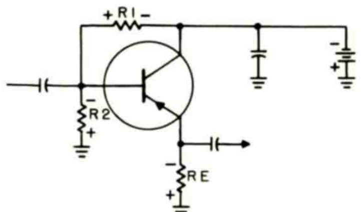
COMMON-EMITTER BIAS CIRCUIT
FOR "NEGATIVE GROUND" SUPPLY

FIGURE 2



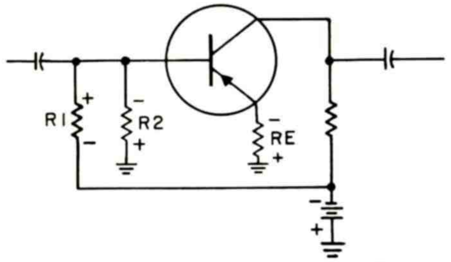
COMMON-BASE BIAS CIRCUIT
FOR "POSITIVE GROUND" SUPPLY

FIGURE 7



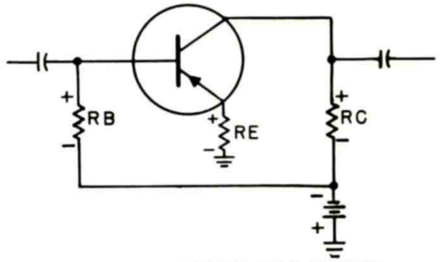
COMMON-COLLECTOR BIAS CIRCUIT
FOR "POSITIVE GROUND" SUPPLY

FIGURE 8



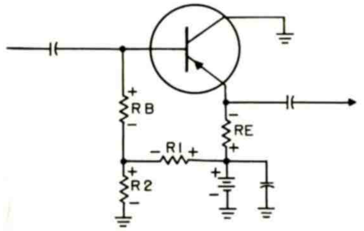
COMMON-EMITTER BIAS CIRCUIT
INCLUDING EMITTER RESISTOR

FIGURE 3



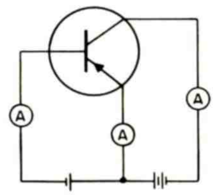
COMMON-EMITTER BIAS CIRCUIT

FIGURE 4



COMMON-COLLECTOR BIAS CIRCUIT
FOR "NEGATIVE GROUND" SUPPLY

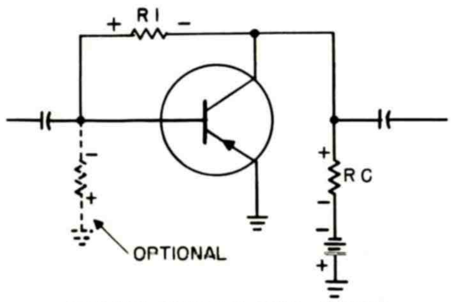
FIGURE 9



AMMETERS PLACED IN THE EMITER, COLLECTOR AND BASE CIRCUITS SHOW AN INCREASE OF CURRENT WITH AN INCREASE OF TEMPERATURE.

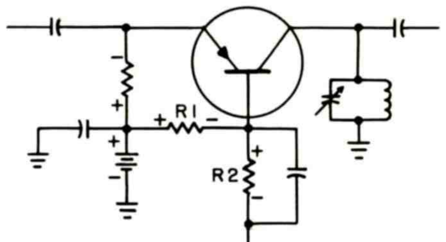
TRANSISTOR CURRENTS VS TEMPERATURE

FIGURE 10



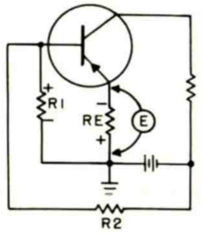
COMMON-EMITTER BIAS CIRCUIT
--COLLECTOR—BASE RESISTOR--

FIGURE 5



COMMON-BASE BIAS CIRCUIT
FOR "NEGATIVE GROUND SUPPLY

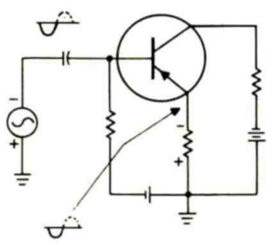
FIGURE 6



VOLTAGE E OPPOSES OR COUNTERACTS THE BIASING VOLTAGE. AS E INCREASES THE FORWARD BIAS DECREASES AND VICE VERSA.

TEMPERATURE STABILIZATION OF DC
OPERATION BY UTILIZING EMITTER RESISTOR

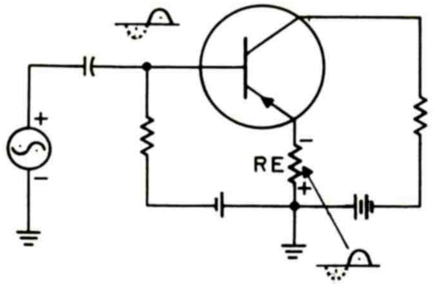
FIGURE 11



1. ON NEGATIVE SIGNAL SWING THE FORWARD BIAS INCREASES.
2. THE EMITTER CURRENT INCREASES.
3. THE EMITTER-GROUND VOLTAGE INCREASES.
4. THE EMITTER SWINGS MORE NEGATIVE.
5. THE NEGATIVE GOING EMITTER OPPOSES THE ORIGINAL CURRENT INCREASE.

SIGNAL DEGENERATION DUE TO
EMITTER RESISTER ON NEGATIVE INPUT

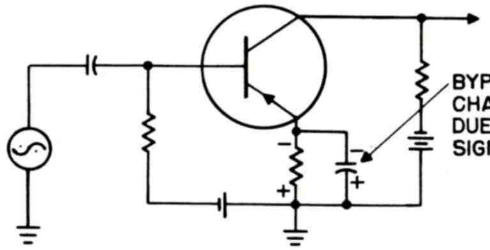
FIGURE 12



1. ON POSITIVE SWING OF SIGNAL THE FORWARD BIAS DECREASES.
2. THE CURRENT AND VOLTAGE AT THE EMITTER RESISTOR ALSO DECREASE.
3. THE EMITTER SWINGS POSITIVE (LESS NEGATIVE TO ⏚).
4. THIS POSITIVE EMITTER SWING OPPOSES THE ORIGINAL REDUCTION IN CURRENT.

SIGNAL DEGENERATION DUE TO
EMITTER RESISTOR--DURING POSITIVE INPUT

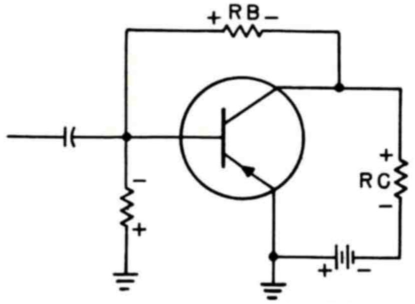
FIGURE 13



BYPASS CAPACITOR PREVENTS ANY CHANGES OF VOLTAGE AT EMITTER DUE TO CURRENT VARIATIONS AT SIGNAL FREQUENCIES.

EMITTER BYPASS AVOIDS
DEGENERATION

FIGURE 14



1. AS TEMPERATURE INCREASES BOTH THE CURRENTS AND VOLTAGES OF RC AND RC INCREASE.
2. THE BASE IS NOW LESS NEGATIVE, OR, IN EFFECT IT HAS SWUNG POSITIVE.
3. THE FORWARD BIAS IS DECREASED, OPPOSING THE ORIGINAL CURRENT INCREASE.

DC STABILIZATION, USING
COLLECTOR-BASE RESISTOR

FIGURE 15

national
MOTOROLA
RADIO COMMUNICATIONS
service

A TWO-WAY RADIO COMMUNICATIONS TRAINING PROGRAM

LESSON SA-6
TRANSISTORS

Transistorized Audio Equipment

MOTOROLA TRAINING INSTITUTE

A TWO-WAY RADIO COMMUNICATIONS TRAINING PROGRAM

LESSON SA-6
TRANSISTORS

Transistorized Audio Equipment

—one of a series of lessons on two-way FM communications—

MOTOROLA TRAINING INSTITUTE
4501 W. AUGUSTA BLVD., CHICAGO 51, ILLINOIS
APPROVED BY THE STATE OF ILLINOIS
DEPT. OF REGISTRATION AND EDUCATION

PREFACE

This is one lesson of a complete Motorola Home-Study Course which presents to the Service Technician both the principles of operation and the maintenance of two-way FM radio systems. The program covers mobile, portable and base station equipment, including the latest transistorized units.

TRANSISTORIZED AUDIO EQUIPMENT

LESSON SA-6

TABLE OF CONTENTS

NOTICE

Diagrams and figures referenced in text are "fold-outs" in back of each lesson, for use while studying. The Examinations are also there.

A transistorized "Power Voice" megaphone is used by shipyard dockmaster. The high audio output of unit enables him to direct drydocking of coastal vessel.

TRANSISTORIZED AUDIO EQUIPMENT

Lesson SA-6

Introduction

In our study of the transistor thus far, we have learned about its basic principles of operation; we found that the transistor is a current controlling device. That is, the gain of the transistor amplifier depends upon both the current gain and the impedance gain of the transistor. We also learned about the three configurations which may be used in amplifiers, being the common-base, common-emitter, and common-collector circuits. In studying transistors we also discovered that the same methods and problems of coupling encountered with vacuum tubes apply to transistor stages.

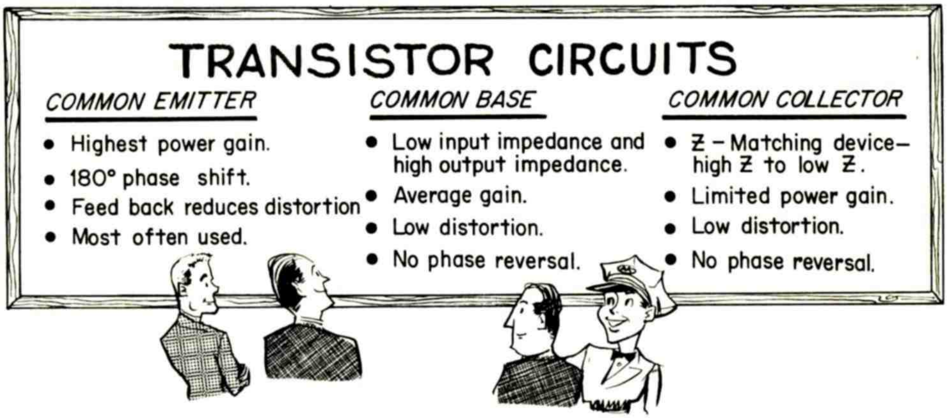
In this lesson we shall apply what we already know to various low-frequency circuits found in Motorola communications equipment. While we have talked about low-power transistors thus far, in this lesson we shall also discuss transistors and audio stages capable of greater amounts of power. Before proceeding with these matters, however, we shall make a short review of transistor operation.

Transistor Circuits and Characteristics (Review)

The chart of figure 1 summarizes the characteristics of the three transistor circuits. Due to its high current gain and medium impedance gain, the common emitter gives the greatest power gain, requires the least amount of input power for a given power output, and is the most often used. The common-emitter circuit gives a phase shift of 180° from its input to its output, although there are but few applications where this is of particular importance.

There is one disadvantage of the common-emitter arrangement, in that it gives the greatest amount of distortion. Due to its high gain, however, it is possible to introduce feedback, thereby reducing the distortion but, at the same time, maintain a reasonable gain.

There are certain applications where the common-base circuit is the most satisfactory to use-- where the source impedance is low and the load impedance high. The gain of the common-base circuit is average, the distortion is rela-



Each Transistor Circuit Has Its Specific Characteristics and Application.

tively low, there is a medium amount of isolation between the input and the output circuits, and there is no phase reversal between the input and output signals.

The common-collector circuit finds its main application as a means of impedance matching a high-impedance source to a low-impedance output. There is no voltage amplification for this stage and only a limited amount of power gain. In addition, the input and output circuits are very interactive, the distortion is low due to the high amount of feedback inherent to the circuit, and the output signal is in phase with the input.

Coupling Methods (Review)

We found in our study of coupling methods that the same problems and methods of coupling inherent to vacuum-tube circuitry are applicable to transistor stages. For audio circuits, RC and transformer coupling are the most popular, although direct coupling is also sometimes employed.

Transformer coupling has the advantage of providing an impedance match which, in turn, allows maximum gain. Transformers, however, are relatively expensive and are not conducive to the construction of lightweight, compact equipment. Transformers have their greatest application where the audio signal is relatively large and the power level is high.

RC coupling is most often used where the signal is small and the power level is low. Thus, in audio equipment, we expect to find RC coupled stages as the first few stages of the amplifier, but not in the final stages. In general, RC circuitry is used where the power level is below 100 milliwatts (0.1 watt). For high power stages, transformers are usually necessary.

Direct coupling is also encountered in certain audio equipment, but it is not used extensively because of the difficulty of providing temperature stability. We will see at least one application of DC coupling as we study the various audio stages of Motorola equipment.

We have just completed our brief review of transistor circuitry and are ready to proceed with our study of transistorized audio amplifiers. The first new subject matter to be discussed is feedback and distortion.

Feedback and Distortion

It is common practice to use degenerative feedback to offset the distortion inherent to transistor amplifiers. In addition to providing degeneration, the feedback often gives DC stabilization. The reduction of distortion due to degenerative feedback is approximately equal to the loss in gain. In the preceding lesson we found two types of DC stabilization which could also be used to provide a certain amount of degenerative feedback. These are the unbypassed emitter resistor and the resistor between the collector and base.

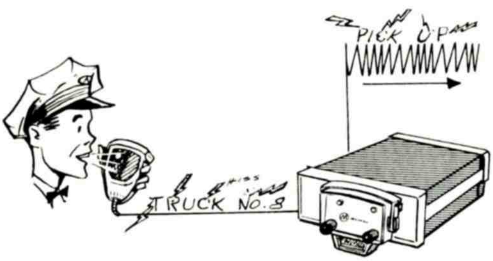
Referring to figure 2, the varying voltage across an unbypassed emitter resistor in the common-emitter circuit reduces the effective signal voltage between the base and emitter, thereby lowering the over-all stage gain. However, the distortion is reduced by a nearly equal amount. The reduction in gain due to the emitter resistor depends on the source and load impedances as well as on the value of the resistor and the characteristics of the transistor. This emitter resistor has the effect of raising the input and output impedances.

Figure 3 shows another type of degenerative feedback commonly encountered in the common-emitter circuit. Feedback resistor RF applies some of the output voltage to the input, and this feedback voltage is of such phase to oppose the signal voltage.

Consequently, the effective signal voltage is reduced and the gain is lowered. This feedback reduces the input and output impedances instead of raising them as in the case of the unbypassed emitter resistor.

In the above arrangements, distortion is reduced by introducing degenerative feedback within a single stage. Feedback (and consequent improvement in amplifier response) can also be applied around a number of stages, but far more care in design is required. In general, greater stability and control of the amount of reduction of distortion can be obtained by introducing the feedback within an individual stage. Feedback introduced by this method is more effective over the entire audio range, and the response is more linear.

Where a feedback loop is provided for three or more stages, phase shift within individual stages at the higher frequencies is likely to produce sufficient regeneration to cause oscillation. That is, the feedback at the lower frequencies may be degenerative, but the phase shift at the higher frequencies may be regenerative and cause oscillation.



Without a Preamplifier, the Weak Audio Signal from the Microphone Must Compete with the Noise Pickup in the Audio Lines.

Transistorized Microphone Preamplifier

The dynamic microphone and preamplifier has two distinct advantages over the previously used carbon microphone: there is (1) a decided improvement in frequency response and (2) less background noise. Because of the relatively low output of the dynamic element, however, it is necessary to provide an additional stage of amplification.

The transistor affords a very practical means of locating the amplifier right in the microphone housing rather than at the transmitter chassis; this allows a better signal-to-noise ratio of the modulating signal. If the amplifier were located at the transmitter itself, any noise picked up between the microphone and the amplifier would be amplified right along with the audio. By using the preamplifier in the microphone housing, the audio signal is built up before any noise is introduced and there is no need for any additional preamplification at the transmitter chassis. The audio signal may now be applied directly to the audio section of the transmitter.

The transistor requires only a low value of DC voltage and current for its operation, and it is practical to supply this through the microphone cable. In fact, the DC formerly supplied to the carbon microphone element may be used for the amplifier. This arrangement is not so simple for a vacuum-tube preamplifier, where both filament and plate power are required.

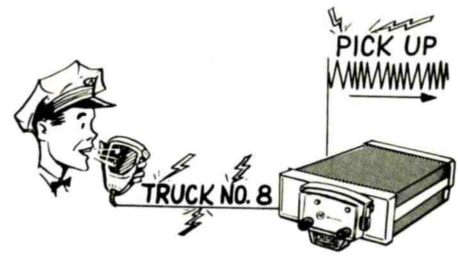
The microphone preamplifier shown in figure 4 is very similar to those which we have been discussing in the preceding lessons. A PNP low-power transistor is used in a common-emitter circuit; junction bias is provided by the voltage divider consisting of resistors R1 and R2. The emitter-base bias is the voltage of R1 less the voltage developed across stabilizing resistor RE. The voltage across R2 is the collector-base reverse bias.

The electrolytic condenser prevents degeneration of the audio signal across the emitter resistor and allows for maximum gain. The return path for the base is through the dynamic microphone element. The microphone has a low impedance, about 50 ohms, which provides for an easy match to the input of the amplifier.[1]

A small, 10-ohm resistor in the emitter return circuit, which may be shorted out at the factory when the microphone is tested, affords a means of compensating for the normal variations of gain which occur in transistors of the same type.

This resistor is not bypassed and hence it is degenerative if left in the circuit. For transistors of average gain, then, the resistor must be shorted so that the amplifier has full gain; for transistors of high gain, however, the short is removed so that the resistor is in the circuit and the gain of the stage is reduced. This resistor allows all microphones, in connection with their preamplifiers, to have the same output voltage, the design center being 0.17 volt.

If microphones of widely varying output voltages are used with a particular transmitter, one of two conditions will occur. First, if the deviation of the transmitter is adjusted according to a microphone having a high output, other microphones with less output voltage will not produce full deviation, and they will sound weak and possibly noisy in the receiver.



A Preamplifier Produces a Strong Audio from the Microphone, Thereby Avoiding the Problem of Noise Pickup.

Second, if the transmitter deviation is adjusted according to the output of a "weak" microphone, other microphones having higher output voltages will overdrive the IDC circuit and cause excessive clipping. This produces nonlinear deviation at the transmitter, which means unnecessary distortion of the message at the receiver.

The output voltage of the dynamic microphone and its preamplifier has about the same amplitude as the carbon microphone and can be substituted directly for the carbon microphone in almost all Motorola transmitters. (It may be necessary to readjust the IDC control.)

Transistorized IDC Circuit

Portable Motorola equipment includes a transistorized version of the IDC (Instantaneous Deviation Control) circuit. The purpose of this section of the transmitter

1. See Basic Theory and Application of Transistors (TM11-690), pages 112-116

is the same regardless of whether we use vacuum tubes or transistors. That is, the amount of deviation produced at the modulator must be limited to a specific amount and, as we know from our previous discussions about IDC, this requires a control of both the amplitude and the waveform of the modulating signal. (An increase of either frequency or amplitude of the modulating signal at the phase modulator increases the amount of deviation.)

Figure 5 shows the arrangement of the transistorized IDC circuit. Only one stage is used; it provides a certain amount of amplification for the small audio input, but it also limits the output of stronger signals. The 2N217 transistor used as the amplifier-clipper is a low-power, PNP unit. The B supply is used as the bias voltage source with R3 providing the necessary drop to 9 volts, the actual supply voltage for the stage. Voltage divider R1 and R2 plus emitter resistor RE provide the optimum emitter-to-base bias.

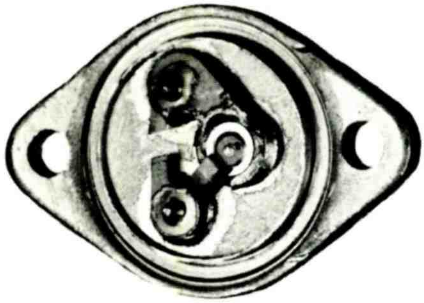
The base is less positive than the emitter, so the emitter junction is forward biased and allows collector current. As soon as current is established through the emitter resistor, the resulting voltage drop makes the emitter less positive and the emitter junction forward bias is reduced. The difference between the base and emitter potentials is the effective bias voltage, in this case 0.1 volt.

The over-all action of this circuit is essentially the same as that of the corresponding vacuum-tube version. The transistor provides amplification for signals below a predetermined level, but for those signals above this level the transistor goes into clip--the output voltage cannot increase above a certain predetermined level. (We shall speak of this limiting action in greater detail in the next lesson.)

Following the clipper, the integrator and the splatter filter further alter the audio waveform to resemble a sinewave, thereby reducing the harmonic content of the wave and avoiding overdeviation, splatter and distortion.

One more factor in this circuit, is the natural 6-db per octave deemphasis characteristic of the integrator. In order to maintain a flat response within the stage, a differentiator is included in the input, and this has a 6-db per octave preemphasis. In figure 4 this differentiator is capacitor C1 and the input impedance (resistance) of the transistor.

Figure 5 includes the waveforms which result from signals above and below the clip level. Sinewaves having considerable amplitude become square waves at the collector and triangular waves at the modulator input. Signals which are partially clipped become more trapezoidal at the collector and more sinusoidal at the output.



The Power Transistor is Large and Usually Has Its Collector Grounded to the Frame for Efficient Heat Dissipation.

The output of the transistor (the collector circuit) has a low impedance (about 10,000 ohms) compared to the inherently high impedance of the modulator grid. Transformer T1 provides for this difference of impedance; it has a primary of 10,000 ohms and a 250,000-ohm secondary. R4 and C2 comprise the integrator; L1 and C3 make up the waveshaping circuit, limiting the high-frequency energy and hence the splatter.

Potentiometer R5 at the output is the IDC control. It is preset at the factory and need not be readjusted unless there has been some reason for changing it. Where the transmitter is improperly deviated, it is best to locate the original source of the trouble and to correct it, rather than compensate for the trouble by means of the IDC pot.

This completes our discussion of transistorized low-power audio stages. The next audio stages to be discussed make use of transistors capable of handling a considerable amount of current and power. We shall now have a look at these transistors and their operating characteristics.

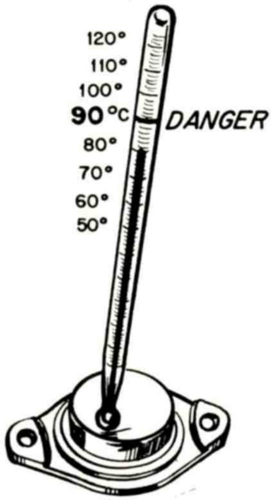
Power Transistors

Power transistors are physically much larger than the "low-power" transistors we have been discussing up to this point. The transistor elements alone does not require any great space, but the associated assembly is made large in order to provide for good heat conduction. The currents which pass through the junctions generate considerable heat, and this heat must be dissipated if the transistor is to operate as intended.

A close inspection of the power transistor shows one of its elements (usually the collector) in physical contact with the transistor mounting base. This helps to transfer the heat away from the junction to the mounting base, and from the mounting base the heat is transferred to a "heat sink," whence it is radiated into the surrounding space.

In order to provide good heat transmission away from the junction (as well as good electrical conduction), copper and similar materials are used extensively in the construction of power transistors. The semiconductor material from which the transistor is made has a lower heat conduction than copper, which partially accounts for the higher temperature at the collector junction.

The maximum recommended junction operating temperature of the average power transistor is approximately 90°C (194°F). This temperature rating is determined not by the physical construction of the transistor, but by a gradual deterioration known as "aging."



The Temperature (Internal) of Germanium Power Transistors Should Not Exceed 90°C.

At temperatures above 90°C, but still below the melting point of the transistor materials, both the normal increase of the internal leakage current (I_{CO}) and the accompanying decrease in current amplification (h_{fe}) are accelerated, so that the transistor ages prematurely and the unit soon becomes inefficient. This 90°C rating thus represents a compromise between power dissipation and the accelerated aging of the transistor.

The maximum permissible collector junction dissipation is determined by the ambient temperature. Any power dissipated in the collector junction causes an increase in temperature. Therefore, if the ambient temperature is already the maximum which is allowed, any further increase, due to collector dissipation, will overheat the transistor. Thus, the ambient temperature must always be less than the maximum allowed temperature.

Power Transistor Limitations

The operation of power transistors is limited by two inherent characteristics. First, the current amplification factor changes with the emitter current. Second, the input impedance is not linear.

Figure 6 shows the variations in amplification factor exhibited by power transistors as the emitter current increases. Consider first the curve for the "non-doped" junction. With an emitter current of less than one-half ampere, the amplification factor (h_{fe}) is greater than 50. As the emitter current increases, however, the amplification factor decreases; for currents greater than 3 amperes, the amplification factor is less than 10. These values are for power transistors having indium emitters.

When a small amount (about 2%) of aluminum or gallium is added to the emitter, the amplification factor of the transistor does not decrease as rapidly for increases of emitter current. Consider the curve for the "doped" emitter junction in figure 6. At currents greater than 2 amperes the amplification factor is at least twice that of the non-doped junction. Also important is the fact that the doped junction shows considerably less over-all change in its amplification factor between low and high values of current.

The nonlinear input impedance of power transistors is also an important consideration. If we are to avoid distortion in the output as a result of this nonlinear input impedance, it will be necessary to establish a sinusoidal change in the input current; it is not sufficient merely to apply a sinusoidal voltage.

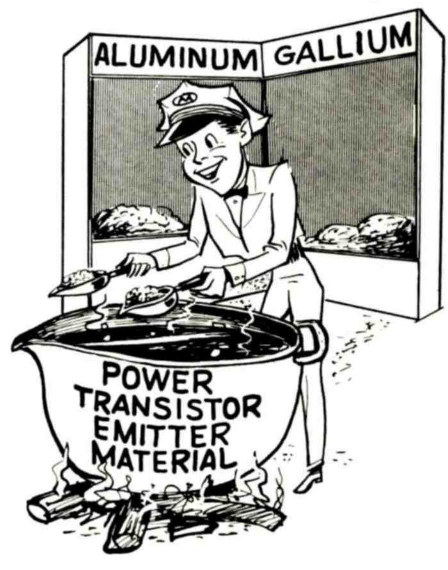
If the impedance of the source is high compared to the input impedance of the transistor, the change of impedance within the transistor will have but little effect upon the current. The end result is that a sinusoidal signal voltage will cause similar current variations.

The degree of non-linearity of the input impedance varies with the transistor configuration. The common-emitter circuit shows a greater variation of input resistance than either of the other configurations, so it is likely to cause the most distortion in the average circuit.

While the common-collector and common-base configurations cause less distortion, they also provide less power gain than the common emitter. Thus, the choice of circuitry depends upon the stage requirements; we must sacrifice one or the other, either gain or distortion.

The Power Amplifier

Most of the problems encountered in vacuum-tube power amplifier stages, such as class of operation, impedance matching and distortion, are found also in the transistorized audio power amplifier. The transistor, however,



A Small Amount of Aluminum or Gallium Added to P-Type Emitter Material Provides a More Constant Current Gain in Power Transistors.

has the additional problem of heat dissipation, which is more critical in transistors than in vacuum tubes.

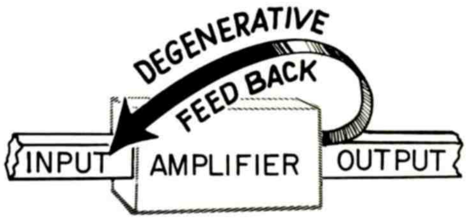
Where a single-ended stage is used, the transistor is operated in Class A in order to keep the distortion at a minimum. Where a greater power output (at higher efficiency) is required, push-pull stages are used. The output transformer must be able to handle the transistor currents, and the transformer turns ratio must provide a suitable match between the output impedance of the transistor and the impedance of the load.

Class A Operation

Where a transistor is operated in Class A, either single-ended or push-pull, the average current does not change appreciably when a signal is applied. With the transistor constantly conducting current, there is heat being generated at all times and this heat limits the power output of the stage.

In Class A operation, only a small amount of the power taken from the supply reaches the speaker (to be converted into acoustical energy). Thus, if we are to have an output of 10-15 watts, the power transistor in the output must be capable of handling a very large collector current.

When the transistor is operated in Class A, the emitter current



Degenerative Feedback Serves Two Purposes: It Reduces Distortion and Stabilizes the Amplifier.

approaches cutoff and maximum on the positive and negative peaks if any great amount of power is to be delivered to the load. This means that the emitter current varies over its complete range. As we saw (in figure 6), the current gain of the transistor varies with the emitter current and, as a result, one alternation will always be amplified more than the other--the two alternations will not have equal peaks in the output. This asymmetrical output constitutes a very undesirable form of distortion; it limits the permissible swing of the input signal to the final amplifier.

Push-Pull Amplification

The push-pull power amplifier is a solution to many of the problems associated with the single-ended Class A transistorized amplifier. But, while the transistorized push-pull stage is often described as "Class B," we shall soon see that the operation is more likely to be in Class AB.

Let us first consider the operation of the push-pull Class B transistor amplifier. With no signal applied, each transistor is biased at approximately cutoff and there is very little emitter current. Hence, there is no appreciable amount of heat dissipated in the transistors.

When a signal is applied, each transistor conducts on one alternation, thus operating only half the time; even then the amount of current is determined by the strength of the applied signal. As a result of this class of bias, the average amount of heat generated within the transistor is considerably less than for Class A stages. At the same time, considerably more power output (load power) is realized from the arrangement. Two transistors operating in push-pull, Class B, can deliver about 3.5 times more output power than one transistor of the same type operating Class A.

Figure 7 shows why the push-pull transistor amplifier should not operate in strict Class B, with each transistor biased at cutoff. The transfer characteristic at A applies to Class B, push-pull operation of transistors. At the crossover from one transistor to another, the output current does not start immediately. Moreover, as each transistor completes its half-cycle of conduction, the emitter current reaches zero before the input signal is zero, with the result that there is a discontinuity in the output waveshape (shown to the right in the figure).

The crossover effect, caused by operating the transistors at cutoff, can be overcome by biasing the transistors so that they are slightly conductive without a signal applied. This bias (somewhere between Class A and Class B) is known as Class AB. The initial current established in the transistor is normally somewhere between 1 and 5 percent of the average emitter current with a signal applied; the exact value depends on the characteristics of the transistor.

The transfer characteristic of figure 7B applies to the push-pull operation of a transistor amplifier in Class AB. There is no discontinuity at the crossover points in the output waveform, and the output is a faithful reproduction of the input.

If the forward bias is too great, as at (C), each transistor becomes conductive over a longer portion of the crossover point and the gain of the amplifier at this point is high. As the signal swings toward its peaks, however, one of the transistors becomes nonconductive; the gain is reduced. This effect is shown both in the nonlinear transfer characteristic and in the nonsinusoidal output waveform.

Thus, the operating point of the push-pull amplifier is very important. If we are to avoid distortion in the output, it will be necessary to stabilize this operating point for all changes in temperature.

Temperature stabilization was discussed to some extent in the preceding lesson. The same principles may be applied to the power amplifier so long as the resistor in the emitter circuit is kept at a low value of resistance. (Otherwise, the resulting power loss in the resistor will be intolerable.)

The stabilizing resistor may be bypassed in single-ended or push-pull Class A stages in order to avoid degeneration and loss in gain. The resistor cannot be bypassed, however, in Class AB or Class B push-pull stages. Without the bypass capacitor, the voltage across the resistor varies with the instantaneous current, so that the only effective bias for the stage is that establishing the original bias.

With a bypass capacitor connected across the stabilizing resistor, however, there will be a DC voltage established across the resistor, and this voltage will change with the input signal and with the emitter current. This variable DC voltage produces an additional (and changing) bias on the transistor.

Another source of distortion in the push-pull amplifier is mismatch between the transistors, particularly with respect to their current amplification characteristic. The circuit configuration makes considerable difference in the amount of distortion which results from this mismatch, and the common-collector configuration seems to be the most free from the effects of a mismatch. Although transistors may be matched at the time they are installed, their aging may not be identical with continued operation and a mismatch may eventually occur.[2]

Motorola "Power Voice" Speaker

The average mobile communications receiver, with an audio output limited to a few watts or less, does not drive the speaker sufficiently to overcome loud interfering noises. A practical answer to this problem is the transistorized "power voice" speaker, which operates directly from the vehicle battery. The schematic diagram for the 6/12 volt version of this speaker is shown in figure 8.

The push-pull amplifier operates at Class B, (it is called Class B, but we have just seen that the bias is most likely Class AB); it furnishes 15 watts when operated from a 13.8-volt supply, or 5 watts of power for a 6.6-volt supply. The input to the amplifier is the 3.2-ohm secondary of the receiver output transformer.

The aluminum chassis of the amplifier is the heat sink, for the transistor heat dissipation. The entire amplifier chassis is insulated from the speaker housing, making the polarity of the vehicle's electrical system unimportant. The red lead at the input connects

2. See TM11-690, pages 128-132.

Here We See the Transistors and Heat Sink Chassis of a Motorola Power Voice Speaker.

to the positive side of the supply, black is negative. The other two connections are to the secondary of the receiver output transformer; these connections may be made at the control head.

Only one change is required in the wiring in order to operate the circuit on 6 or 12 volts. This connection is at the output transformer secondary. The speaker is connected across the entire secondary winding for 6-volt operation, and to the tap for 12-volt operation. This changes the effective turns ratio; it also reflects a different load impedance.

At 12 volts the 3.2-ohm load of the speaker voice coil, connected to the tap on the secondary, reflects a high impedance into the primary, for the effective turns ratio is high. The result is that the amplifier delivers the full 15 watts of power to the speaker voice coil.

What happens when we change the applied power to 6 volts without changing the tap? With only half as much voltage we can normally expect only half as much current. The net result, as a matter of fact, is that the power at 6 volts is only one-fourth the original value, a change of 6 db. This is less than 4 watts of speaker power. The power is increased by changing the tap of the transformer secondary, effectively lowering the primary impedance.

When the speaker is connected across the entire winding, the turns ratio of the transformer is lowered--there are more secondary turns than before. With a lower turns ratio, the 3.2-ohm speaker voice coil reflects a lower impedance into the primary. The low impedance permits an increase in the current, therefore increasing the power.

Bias for the stage is provided by resistor R2, which is part of the voltage divider (R1 and R2) connected across the primary source. The 0.33-ohm resistors in each of the emitter circuits provide DC stabilization.

"Power Voice" Megaphone

Figure 9 is the schematic diagram of a portable, battery-operated, transistorized megaphone. This unit operates from ten flashlight batteries and delivers 15 watts of audio power.

Two single-ended stages, each operated in Class A, provide the initial amplification for the low-level signals from the microphone, and they are followed by a push-pull driver stage and a push-pull output stage, both operated near Class B. The speaker has a center-tapped, 10-ohm voice coil, which permits it to be used as the load on the output stage without requiring a matching transformer. Interstage transformer coupling is used to drive both push-pull stages.

This 15-Watt, Battery-Operated Megaphone is Made Possible by the Use of High-Power Audio Transistors.

An impedance-matching transformer is used with the microphone to provide the proper input to the base of the first stage. The volume control "pot" is connected in parallel with the transformer secondary. A resistor and capacitor are connected in parallel and placed in series with the input signal. This favors the high frequencies by attenuating the lows; the upper voice frequencies pass without attenuation and the reproduced "message" is made more intelligible.

The first two stages use a common-emitter arrangement, with direct coupling between stages. The output of the second stage is applied to the primary of transformer T1. Resistor R5 between the collector and base provides feedback, both DC and AC, stabilizing the operation of the stage and improving the frequency response.

The secondary of T1 is center-tapped so that push-pull inputs are established at the driver stage. Operated at about Class B, these transistors provide sufficient power to drive the following final amplifier stage.

Both the driver and output stages employ the common-collector arrangement. The 10-ohm resistors in each of the emitter leads of the driver stage provide DC stability to that stage. In the final stage, DC stability is provided by the DC resistance of the speaker voice coil, the same as if a separate resistor were used.

The efficiency of biasing the push-pull stages near Class B can be demonstrated by means of the current drain from the battery supply. With no signal applied (standby operation), the entire circuit draws about 100 milliamperes. At normal voice inputs, the average current drain increases to 1.55 amperes.

Until the trigger switch or the microphone button is depressed, there is no drain on the battery. These two switches (shown in the diagram) are in parallel and they are used to apply the battery voltage to the entire circuit. No warmup time is required for transistors, of course, so the unit is ready for operation the instant either switch is closed.

The biasing system for the power voice megaphone is most interesting; for a simplified diagram of the arrangement see figure 10. As soon as the switch is turned on, the emitter of transistor Q2 is connected to the positive side of the supply line through resistors R6, R7, R9 and R10, and the base of the transistor connects to ground (the negative side of the supply) through resistor R3.

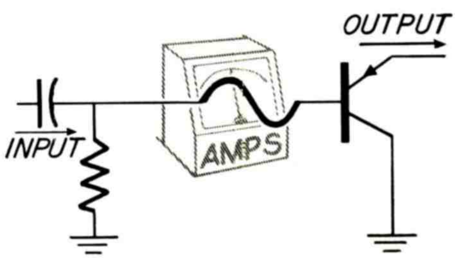
The transistor is now forward biased and conductive. The resulting current (following the positive-to-negative direction) is through resistors R10, R9, R7, R6, the emitter-collector portion of the transistor, and the primary of transformer T1. This circuit becomes a voltage divider across the supply and these voltages determine the forward emitter bias of the other transistor stages.

The voltage across R7 becomes the initial forward bias to Q1 and the transistor conducts. The DC stabilizing voltage across R4 as a result of emitter current alters the final forward bias. A bypass capacitor for R4 in the actual equipment avoids degeneration.

Transistors Q3 and Q4 are biased by the voltage drop across R10. The bases of these transistors connect to the negative side of R10 through the secondary winding of T1 and the emitters connect to the right (positive) side of R10 through the primary winding of T2 and DC stabilizing resistors R11 and R12.

Transistors Q5 and Q6 are biased by the total voltage drop across R9 and R10. The bases of the transistors connect to the left side of R9 through the secondary of T2 and the emitters connect to the positive side of R10, the positive supply line, through the speaker voice coil.

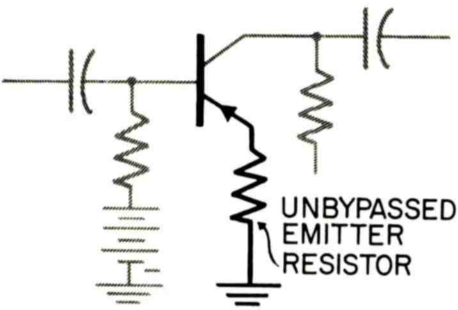
In addition to the audio circuits discussed in this lesson, there is another low-frequency application of transistors which we wish to study--this is the squelch section of Motorola portable and mobile receivers. Before looking at these circuits in detail, however, if you do not recall the principles of squelch operation at this time it may be well to make a quick review of a previous lesson dealing with vacuum-tube squelch circuits.



In Analysing the Transistor Amplifier Input, the Important Consideration Is To Provide a Sinusoidal Current Change for an Applied Sinewave Voltage.

Squelch Circuit of "Portable" Receivers

A large number of Motorola portable receivers, including those of the famous "Handie-Talkie," contain a completely transistorized squelch circuit. As we might anticipate, this squelch is very similar to the vacuum-tube arrangements we have already studied. See the block diagram of figure 11.



The Unbypassed Emitter Resistor Improves the Frequency Response of an Amplifier and Also Reduces Distortion.

Receiver noise, in the absence of a signal, is applied to the noise amplifier, which is followed by a noise rectifier. The DC output voltage of the rectifier, when noise is present, becomes the controlling voltage which biases the audio transistor to the point of nonconduction, thereby closing the squelch. Except for the absence of a DC amplifier between the rectifier and the audio amplifier, this is identical to the vacuum-tube squelch arrangement.

Another difference in the systems is the source of noise voltage. Instead of securing the "noise" from the discriminator, in figure 11 the input to the noise amplifier is the output of the second limiter. We shall discuss this in more detail as we continue with our study of the circuit.

The complete circuit of the transistorized squelch is given in figure 12. Squelch action depends upon a forward or reverse bias at the emitter junction of the audio amplifier. When there is no signal coming into the receiver, the emitter junction of the audio transistor should be reverse biased; when a signal is present, the transistor should be forward biased.

Initial forward bias is established at the emitter junction by returning the base to a fixed negative voltage through resistor R1. With only this voltage applied to the emitter junction, the stage is conductive--the squelch is open. Upon applying a positive voltage to the base circuit (at the upper end of R1 in the figure), the base is made positive to the emitter, the emitter junction is reverse biased, and the stage is nonconductive--the receiver is now squelched.

The positive voltage applied to the control base of the transistor is the output of the noise rectifier. Whenever a high noise level is present in the receiver--when no signal is received--the squelch circuit applies a positive voltage to the base of the audio transistor. When a signal is received, however, the noise quieting of the limiters reduces the input to both the noise amplifier and the noise rectifier, with the result that the positive voltage is removed from the base of the audio transistor and the transistor operates normally--the incoming message is heard.

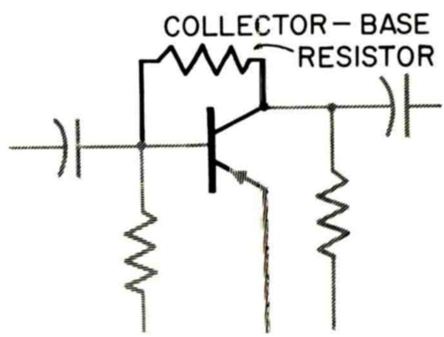
The input to the noise amplifier is taken from the output of the second limiter. A filter (composed of L1, C1, L2 and C2) accepts only the noise components within the higher audio range; the 455-kc IF and the low-frequency voice signals are both attenuated.

This filter is in parallel with C3, which is part of the limiter output. The changes of collector current are not equal for both alternations of the signal during limiting, so that amplitude detection takes place and some AM noise is applied to the noise amplifier. Furthermore, a certain amount of "FM slope detection" takes place for any FM components, either FM noise or FM voice modulations. The input to the noise amplifier is thus similar to that of the noise amplifier of the vacuum-tube squelch circuit, where the input to the noise amplifier is the discriminator output.

The setting of R3 at the input of the noise amplifier determines both the noise level applied to the stage and the output voltage of the noise rectifier. This "pot" is the "squelch control."

The noise amplifier stage, using a PNP transistor in a common-base circuit, is intended to amplify mainly those signals--noise or otherwise--within the upper portion of the audio spectrum. A resistor between the emitter and ground provides DC stability for the stages for changes in temperature; this resistor is bypassed to maintain a reasonable gain.

The output of the noise amplifier is applied to the noise rectifier, which consists of two diodes connected as a voltage doubler and with a positive output voltage. Thus, when noise is applied to the input of the squelch circuit, the positive output voltage from the noise rectifier is applied to the base of the audio amplifier. An incoming signal to the receiver provides noise quieting at the limiters, thereby removing both the noise at the noise amplifier and the positive output from the rectifier.



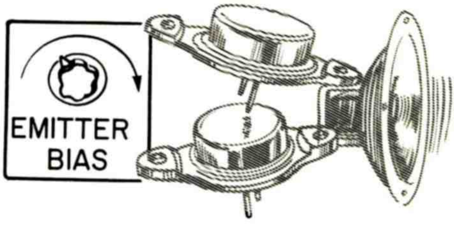
Distortion Can Be Reduced by Connecting a Resistor Between the Collector and Base.

Where the receiver is a part of a complete two-way station, some means is usually employed to disable (mute) the receiver during transmissions. The same idea used to squelch the receiver is employed to mute the receiver during transmission.

The DC return of the noise rectifier is at the lower terminal of CR1 (point A in figure 12), and this connects to the transmitter filament supply line. When the transmitter is turned on, the positive side of the DC supply line to the transmitter filaments is applied, through the diodes, to the base of the audio transistor, thereby reverse biasing the emitter junction and preventing the audio stage from operating. This mutes the receiver during periods of transmission. As soon as this filament voltage is removed, the audio amplifier is again controlled by the squelch circuit.

Transistorized Mobile Receiver Squelch System

Figure 13 shows the block diagram of the squelch system of a completely transistorized mobile receiver. Except for the use of transistors, designated as Q1, Q2, etc., the block diagram is the same as that of vacuum-tube models already studied. Noise from the discriminator is applied to the noise amplifier-limiter, which is followed by a noise rectifier. The DC output of the rectifier controls the operation of the DC control stage which, in turn,



Proper Operation of the "Class B" Push-Pull Audio Amplifier Depends Upon the Correct Emitter Bias.

controls the operation of the first audio amplifier.

The noise amplifier operates as any amplifier-limiter. In the absence of a channel signal to provide noise quieting in the receiver, noise voltages are applied to the input and a predetermined amount of noise appears in the output of the amplifier-limiter. This noise is passed on to the noise rectifier.

The noise rectifier--called a "detector" in the complete circuit--provides a DC output voltage from the applied noise. Because there is a filter in the output of the stage which allows only a DC voltage rather than any signal or changing voltage at the output, we can see why this stage serves the same purpose as the noise rectifier of the vacuum-tube squelch circuits we have already studied.

The DC output of the noise rectifier (present without a channel signal being applied) biases the DC control stage so that it is conductive, and when the DC control stage conducts it drives the audio amplifier stage to nonconduction. Any noise voltages in the receiver circuits cannot get through the audio stage to the speaker. Operating in this manner, the squelch circuit of figure 13 controls the receiver output.

When a signal is received, the opposite effect takes place. The noise input to the rectifier from the amplifier has been removed and hence there is no DC output voltage to drive the DC control stage to conduction. When the DC control stage does not conduct, the audio stage is biased normally and the incoming signal reaches the speaker.

We have just seen the over-all operation of the circuit as analyzed from the block diagram of figure 13. We shall now proceed to inspect the circuit in greater detail, beginning with the bias of the audio amplifier.

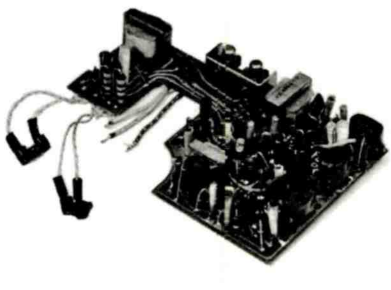
Figure 14 shows how DC control transistor Q3 determines the conduction of the audio amplifier, by altering the emitter bias. When the control transistor is nonconductive it appears as an open circuit, as shown by the open switch. For this condition, the audio amplifier operates in the normal manner and amplifies the incoming signal as desired. When the DC control transistor becomes conductive it acts like a shorted switch in figure 14; it causes the audio amplifier to be reverse biased and nonconductive. Here is what happens.

Resistors R3 and R5 form a voltage divider across the supply and forward bias the emitter junction. Resistor R2 is a stabilizing resistor, producing a voltage drop which opposes the biasing voltage across R3. As we have seen in preceding lessons about transistor bias, the voltage of R3 is normally greater than that of R2 and the emitter junction is forward biased. The incoming signal is amplified and reaches the audio output stages.

When the DC control transistor is conductive (represented in figure 14 by closing the switch) the emitter of the audio transistor is connected to the negative side of the supply line through the switch (emitter-collector section of the transistor).

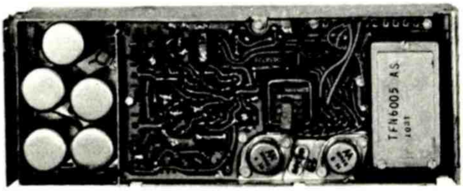
The emitter of Q4 is now negative to the base and the transistor is reverse biased. The transistor is cutoff and noise present in the receiver cannot get through to the speaker.

We have just seen that the operation of the squelch depends upon the conduction or nonconduction of the switch transistor (DC control



Here We See a Typical "Printed Board." This is the Audio and Squelch Section of a Modern Motorola Receiver.

stage). From figure 15 we see that conduction of Q3 may be determined by its base voltage, point C in the figure. If the base is made positive to the emitter, by moving the pot to the bottom of the figure, the transistor is reverse biased and nonconductive. This is the same condition as the open switch shown in figure 14.



This Modern Two-Way Communications Receiver Includes Two Power Transistors (Lower Right). The Cast Aluminum Frame Makes an Efficient Heat Sink.

In order to make the transistor conduct, the pot is moved to the upper end. This forward biases the transistor and allows it to conduct, duplicating the "closed switch" condition of figure 14. Of course, in the final arrangement there is no pot to be moved and perform this function, but this same action happens electrically to the base voltage. See figure 16.

In figure 16 the base voltage is controlled by the operation of the rectifier stage, Q2. The rectifier, in turn, depends upon an incoming signal (noise) for its operation. Without a signal (noise voltage) the transistor does not conduct; when noise is applied the stage acts like a rectifier and conducts on the incoming negative peaks. Let's see how this effects the operation of DC control (switch) transistor Q3.

When the receiver is turned on, capacitor C1 quickly charges to the full supply voltage, through R1. As soon as the capacitor is charged there is no further current through R1 and no voltage across it. The base of Q3, point C in the circuit, is now at the same potential as the positive side of the supply line. The emitter is less positive, however, due to the voltage drop across R2. The DC control transistor is thus reverse biased and is nonconductive; the audio stage may operate normally until something happens to change the voltage at point C, the base of Q3.

When noise is present in the receiver (in the absence of an incoming signal), the negative alternations of the noise pulses from the noise amplifier drive the base of transistor Q2 negative with respect to the emitter and cause the transistor to conduct. This allows a discharge path for capacitor C1 through the transistor and, at the same time, emitter current through R1 causes the base of Q3 (point C) to swing negative. The base is driven negative with respect to the emitter and transistor Q3 conducts, thereby reverse biasing the audio amplifier and squelching the receiver.

As long as noise voltage is applied to the noise rectifier, the base of the DC control transistor remains negative to the emitter and the squelch remains closed. As soon as the noise input is removed from the rectifier, however, the rectifier no longer con-

ducts and capacitor C1 charges to the supply voltage once more, cutting off the DC control stage and allowing the squelch to open. This is desirable, however, for we know that when the noise is removed there is a signal coming into the receiver and the squelch should be open so that the message may reach the speaker.

We have just seen the basic principles of the transistorized squelch circuit. The only stage which we have not analyzed in detail is the amplifier-limiter, and this operates in exactly the same manner as the vacuum-tube amplifier-limiter in other receivers. By having a certain predetermined maximum output voltage regardless of the nature of the incoming signal, the noise rectifier has a relatively constant noise voltage applied when there is no signal. The limiting function of the stage serves to avoid clamping of the squelch in the presence of weak or over-modulated signals. Clamping is covered in the previously mentioned squelch lesson.

The complete circuit of this squelch system is given in figure 17. Although there are more component parts in the various stages compared to the simplified circuits we have been discussing, the operation of each stage is still the same; these added parts assure stable, positive operation.

In the biasing circuit for the base of audio transistor Q4, we see four resistors in series. One of these, R6, is a Varistor and is sensitive to changes of voltage. In fact, this resistor changes its resistance with changes of applied voltage and in this manner maintains constant bias voltages and operation of the stage.

There is a DC filter in the base circuit of the DC control stage which provides a steady DC voltage from the rectified noise pulses at the rectifier output. The time constant of this filter is sufficiently long to prevent the voltage from varying with sudden changes of input signal.

In order to prevent the squelch circuit from clamping, some upper-frequency voice energy is introduced into the amplifier-limiter. The input to the squelch circuit from the discriminator is taken ahead of the deemphasis filter and higher voice frequencies have a higher than normal amplitude. These voice signals overdrive the limiter and block it as far as noise signals getting through are concerned. Thus, the output of the noise amplifier-limiter is nearly free from noise energy when voice modulation is present; as a result, very little noise reaches the rectifier. The squelch cannot clamp in the presence of a modulated signal, for the noise level at the squelch cannot increase during modulation.

Although voice energy is desirable in the amplifier stage, in order to prevent clamping, it is equally as undesirable for this voice energy to reach the noise rectifier and produce an output voltage, for this would cause clamping. The coupling circuit between the amplifier and the rectifier, the "peaking coil" L1 in particular, attenuates the low-frequency voice signals and prevents them from reaching the rectifier.

This concludes our discussion of low-frequency applications of transistors. In our next lesson we will deal with high-frequency circuits.

STUDENT NOTES

STUDENT NOTES

STUDENT NOTES

CIRCUIT	INPUT Z	OUTPUT Z	Z GAIN	VOLTAGE AMPL.	POWER GAIN	CURRENT GAIN		PHASE	EQUIV. TUBE CIRCUIT
COMMON EMITTER	MEDIUM	MEDIUM HIGH	MEDIUM	HIGH	HIGH	HIGH	HIGH	YES	GROUNDED CATHODE
COMMON BASE	MEDIUM LOW	HIGH	HIGH	HIGH	MEDIUM	NONE	MEDIUM	NO	GROUNDED GRID
COMMON COLLECTOR	HIGH	MEDIUM LOW	(LOSS)	NONE	LOW	HIGH	LOW	NO	CATHODE FOLLOWER

FIGURE I

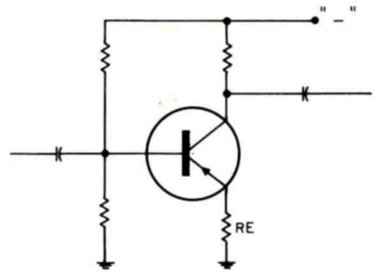


FIGURE 2

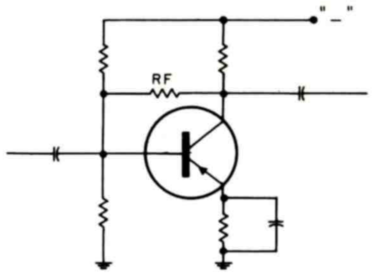
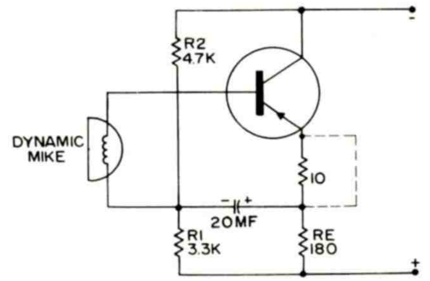
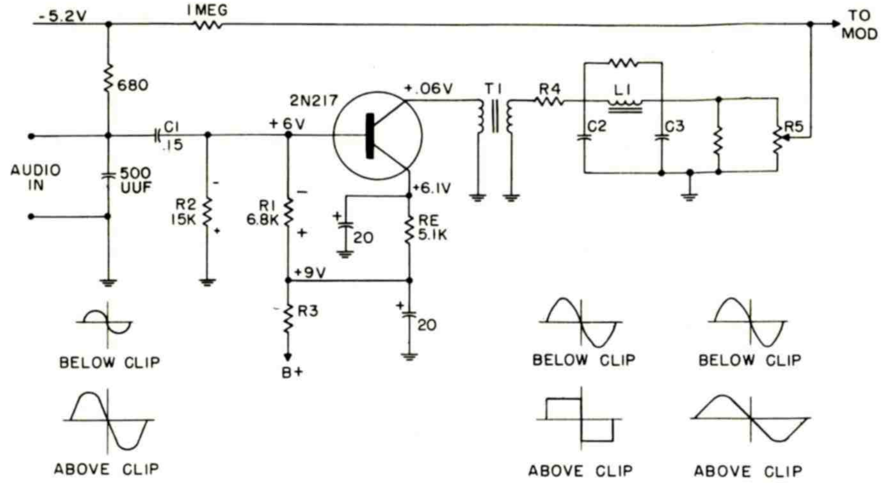


FIGURE 3



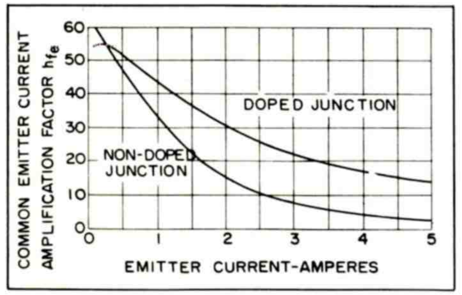
MICROPHONE PREAMPLIFIER

FIGURE 4

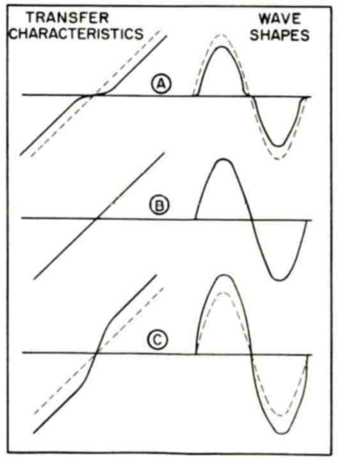


PORTABLE
IDC CIRCUIT

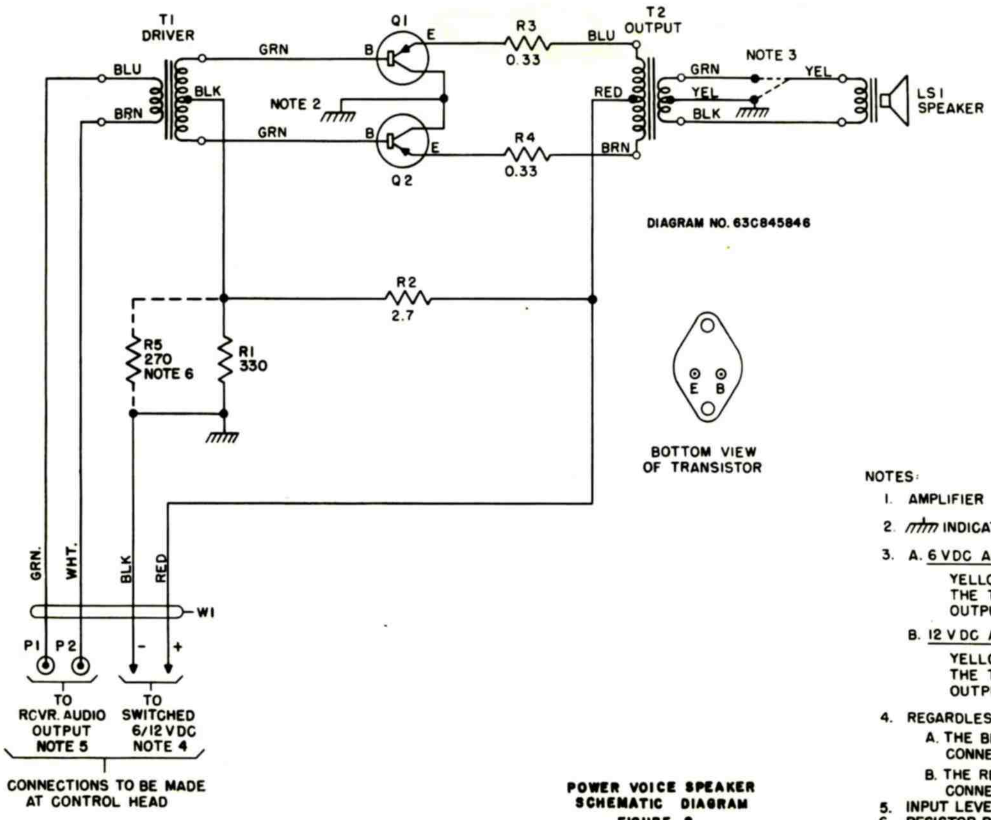
FIGURE 5



COMMON EMITTER CURRENT
AMPLICATION FACTOR vs EMITTER CURRENT
FIGURE 6



CLASS "B" AMPLIFIER
CROSS-OVER DISTORTION
FIGURE 7



POWER VOICE SPEAKER
SCHEMATIC DIAGRAM
FIGURE 8

NOTES:

1. AMPLIFIER CHASSIS IS INSULATED FROM HOUSING.
2. (chassis symbol) INDICATES CONNECTION TO AMPLIFIER CHASSIS.
3. A. 6 VDC APPLICATIONS (TU 433A-6V):
   YELLOW SPEAKER LEAD IS CONNECTED TO THE TIE-POINT OF THE GREEN LEAD OF OUTPUT TRANSFORMER T2.
   B. 12 VDC APPLICATIONS (TU 433A-12V):
   YELLOW SPEAKER LEAD IS CONNECTED TO THE TIE-POINT OF THE YELLOW LEAD OF OUTPUT TRANSFORMER T2.
4. REGARDLESS OF VEHICLE GROUND POLARITY:
   A. THE BLACK LEAD OF CABLE W1 MUST ALWAYS CONNECT TO NEGATIVE (-) SIDE OF BATTERY.
   B. THE RED LEAD OF CABLE W1 MUST ALWAYS CONNECT TO POSITIVE (+) SIDE OF BATTERY.
5. INPUT LEVEL NOT TO EXCEED 1W AT 1000 CPS.
6. RESISTOR R5 IS USED ONLY IN 6VOLT MODEL.

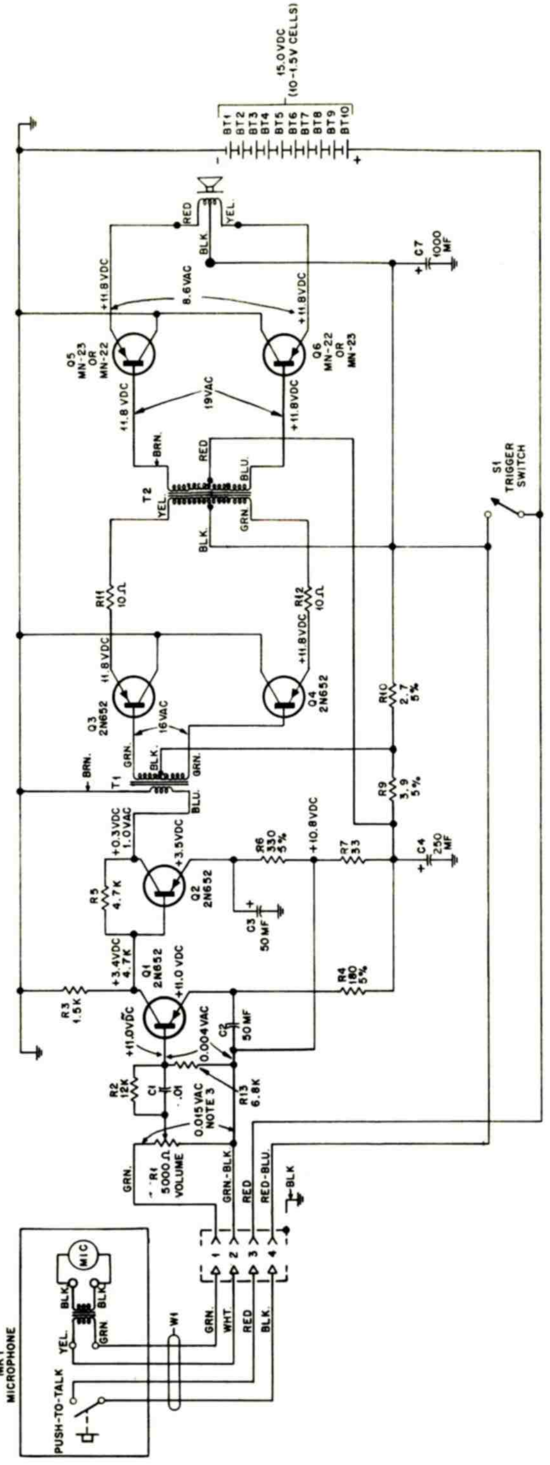
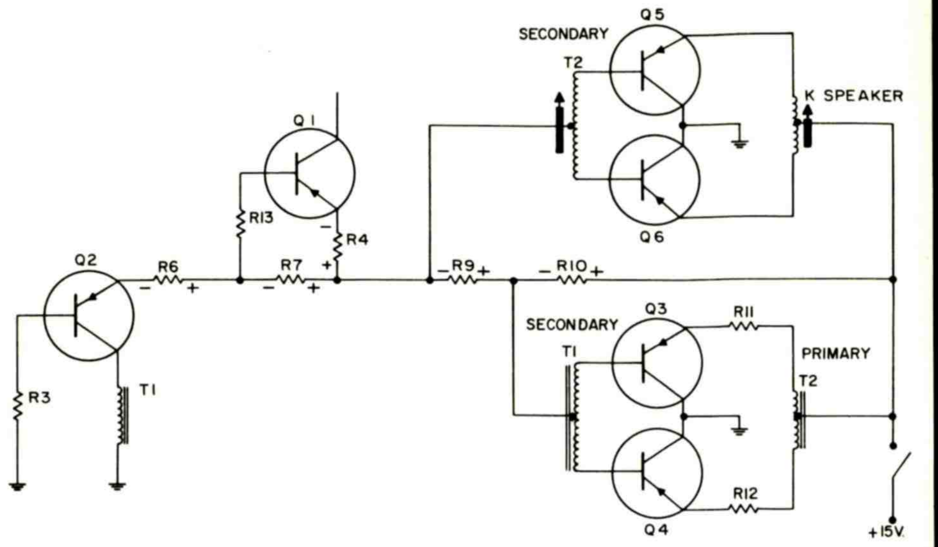


FIGURE 9

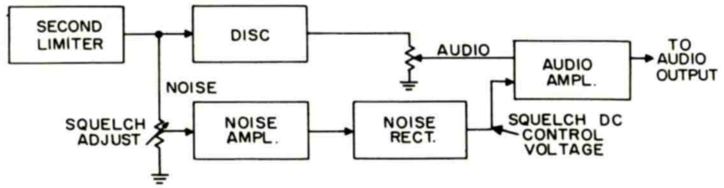
NOTES:

1. ALL VOLTAGE READINGS TAKEN USING A 12VDC SUPPLY.
2. DC VOLTAGES MEASURED TO GROUND WITH ZERO (0) SIGNAL INPUT.
3. AC VOLTAGE MEASURED ACROSS POINTS INDICATED BY ARROWS.
4. ALL OTHER AC VOLTAGES MEASURED FROM GROUND.
5. ALL AC VOLTAGE READINGS MEASURED WITH A 15 MV 1000CPS SIGNAL CONNECTED ACROSS THE VOLUME CONTROL (SET TO MAXIMUM) AND SPEAKER REPLACED WITH DUMMY LOAD WITH 8.6V ACROSS LOAD. (SEE TEXT)
6. ALL RESISTORS 1/2W ± 10% UNLESS NOTED.

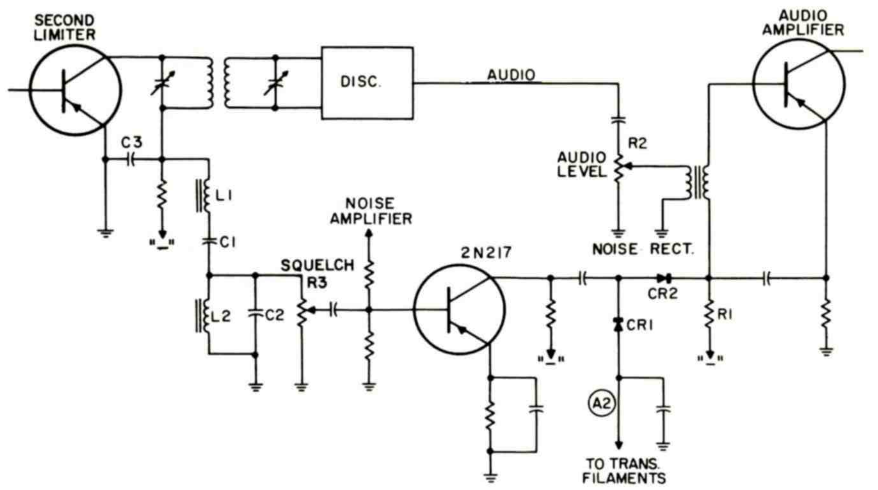


BIAS CIRCUIT
POWER VOICE MEGAPHONE

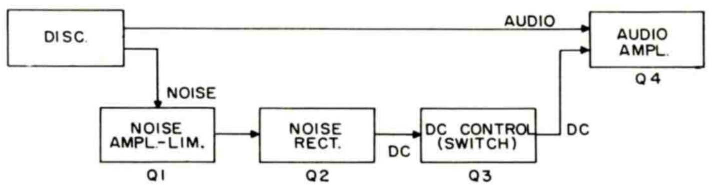
FIGURE 10



SQUELCH CIRCUIT OF
PORTABLE RECEIVER
FIGURE 11



SQUELCH CIRCUIT
FIGURE 12



MOBILE RECEIVER
TRANSISTORIZED SQUELCH
FIGURE 13

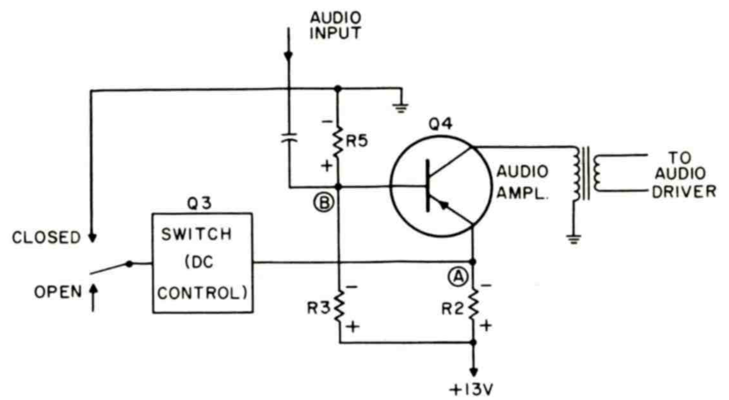


FIGURE 14

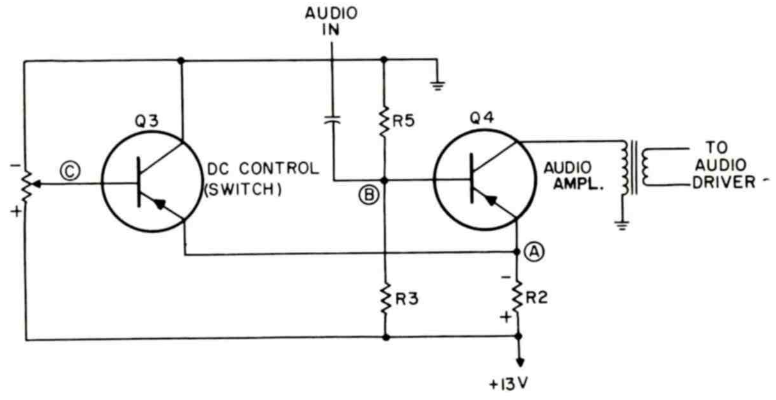


FIGURE 15

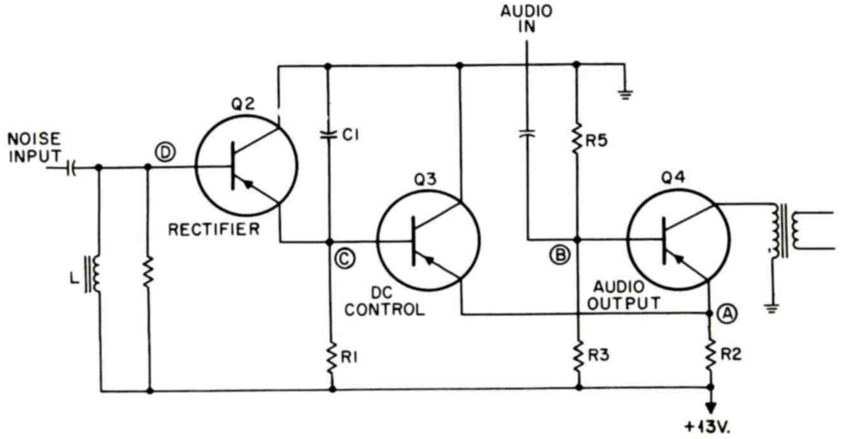
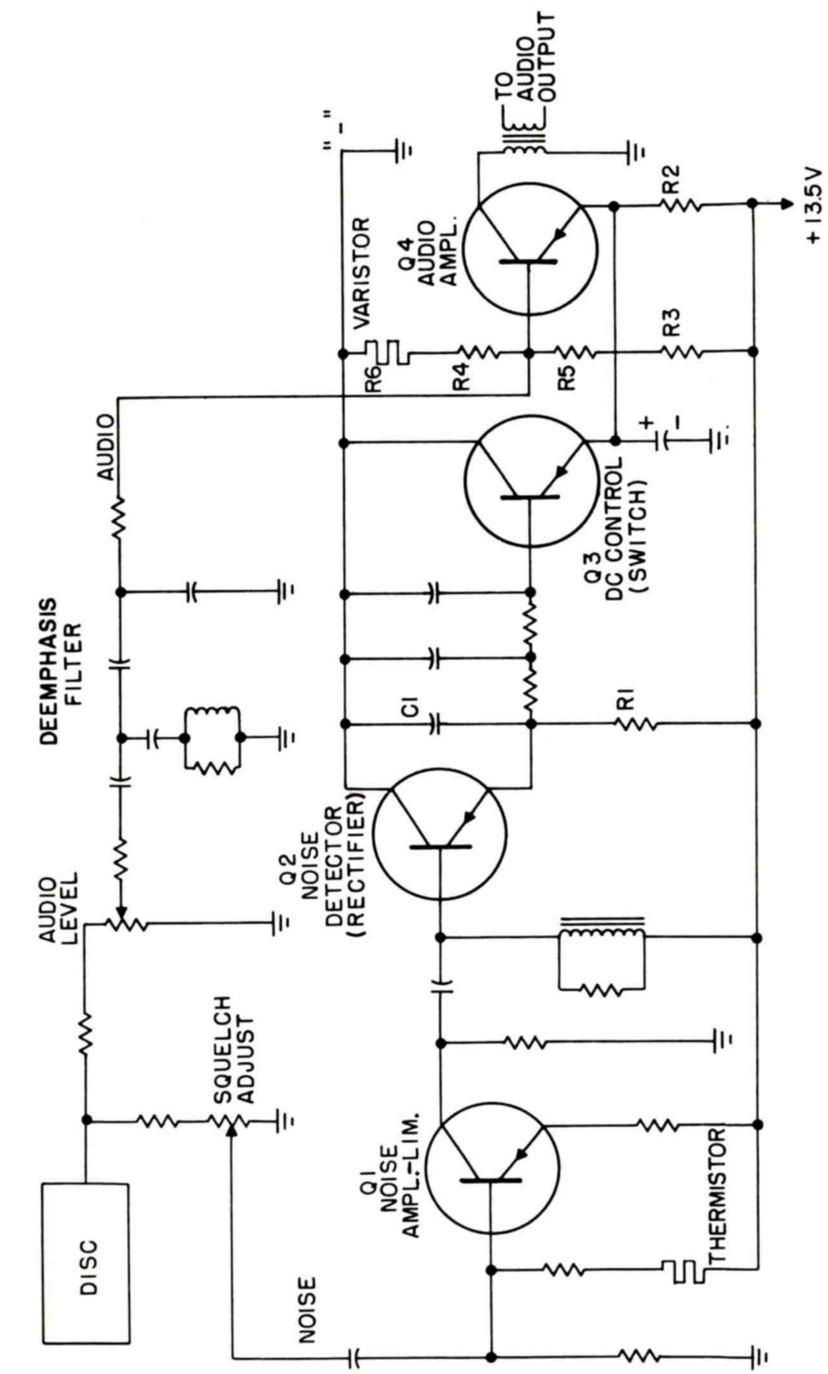


FIGURE 16



COMPLETE SQUELCH CIRCUIT

FIGURE 17

national
MOTOROLA
RADIO COMMUNICATIONS
service

A TWO-WAY RADIO COMMUNICATIONS TRAINING PROGRAM

LESSON SA-7
TRANSISTORS

Transistorized Receiver Circuits

MOTOROLA TRAINING INSTITUTE

A TWO-WAY RADIO COMMUNICATIONS TRAINING PROGRAM

LESSON SA-7
TRANSISTORS

Transistorized Receiver Circuits

—one of a series of lessons on two-way FM communications—

MOTOROLA TRAINING INSTITUTE
4501 W. AUGUSTA BLVD., CHICAGO 51, ILLINOIS
APPROVED BY THE STATE OF ILLINOIS
DEPT. OF REGISTRATION AND EDUCATION

PREFACE

This is one lesson of a complete Motorola Home-Study Course which presents to the Service Technician both the principles of operation and the maintenance of two-way FM radio systems. The program covers mobile, portable and base station equipment, including the latest transistorized units.

TRANSISTORIZED RECEIVER CIRCUITS

LESSON SA-7

TABLE OF CONTENTS

NOTICE

Diagrams and figures referenced in text are "fold-outs" in back of each lesson, for use while studying. The Examinations are also there.

Extensively transistorized two-way units are ideally adapted for use on personnel carriers and other small plant area vehicles. Compactness, reliability, and low battery drain are basic requirements for this application.

TRANSISTORIZED RECEIVER CIRCUITS

Lesson SA-7

Introduction

This lesson is basically a discussion of transistors applied to high-frequency circuits. At the beginning, transistors were restricted to audio and other low-frequency circuits by their inability to amplify at higher frequencies. With improved transistor construction and manufacturing techniques, however, transistorized broadcast-band receivers and other higher frequency equipment became possible. These improved transistors allowed for the transistorization of the last IF section, the squelch section and the audio stages of the communications receiver, such as the Motorola Handie-Talkie two-way portable radio.

Further advances in transistors for high-frequency amplification and operation finally allowed for practical, completely-transistorized two-way radios capable of operating in both the high and low bands.

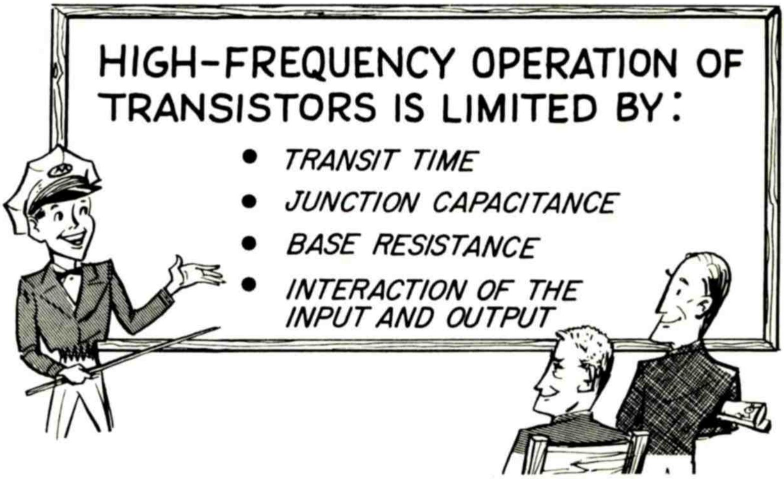
In this lesson we will see the circuitry of the various stages within these receivers. The transistors for these circuits are low-power units, generally falling below the 100 milliwatt rating. It is only when the signal reaches the audio output section of the receiver that transistors capable of more power are required.

High-Frequency Limitations of Transistors

The general purpose, low-power transistor used in low-level audio stages is not suitable for the high-frequencies section of the receiver. These are several reasons why these transistors cannot amplify at high frequencies.

One of the main limitations of high-frequency operation is the time it takes for the carriers to cross the base region, between the emitter and the collector junctions. At higher frequencies less time is required for a complete cycle; if this time period becomes so small that the transit time of the carriers is an appreciable part of the cycle, the amplifier becomes degenerative and is incapable of providing much gain.

Another reason for the high-frequency failure of some transistors is the capacitance of the junctions, particularly that between the collector and base. This



Only a Few Types of Specially Designed and Carefully Built Transistors Will Operate Satisfactorily at High Frequencies.

is usually referred to as the output capacitance. At high frequencies the capacitive reactance at this junction becomes so low that the signal is effectively shorted and it is impossible to develop any signal voltage or power across the output load.

Still another reason for the high-frequency limitation of many transistors as an amplifier is the base resistance. A high resistance makes it difficult to establish much signal current, thereby limiting the gain.

The interaction between the input and the output of the transistor also limits the gain of transistors at high frequencies. Although there is some interaction between the input and output in vacuum tubes, this effect is considerably greater in the transistor.

The degree to which the above limiting factors are controlled or minimized determines the cutoff frequency of the various types of transistors. We shall now discuss briefly various transistor designs in view of these limiting factors.

Alloy-Junction Transistors

The construction of the alloy-junction transistor is illustrated in figure 1. The base is made from a relatively large wafer of N-type material. (An NPN transistor can also be constructed by using a P material for the base.) The collector and emitter junctions are made by placing small pellets of P-type material on opposing sides of the base and heating the assembly until the P material alloys into the base region. The P material penetrates into the N base material, becoming the emitter and collector. By carefully controlling the process, the depth of penetration is regulated and the emitter and collector junctions may be as close as 0.0005 inch.

With an extremely small distance between the emitter and collector, the alloy-junction transistor has a short transit time and is capable of operating at higher frequencies. By utilizing large contact areas to the base, and spaced close to the emitter, the resistance between the emitter and base is kept low and contributes to the ability of the unit to provide high gain. In addition, by using small pellets, the capacitance of the emitter and collector to the base is kept reasonably small and does not prohibit high-frequency operation.

Alloy-junction transistors have an alpha cutoff frequency as high as 25 mc. The corresponding beta cutoff, for a common-emitter circuit, will be around 1 mc. The cutoff frequency indicates the frequency at which the gain has lowered 3 db below the gain at low frequencies. A 3-db decrease is a two-to-one reduction in power output.

Diffused-Base Transistors

The basic idea of diffused-base transistors is to establish an internal field across the base region which accelerates the carriers, thereby reducing the time it takes for the carriers to travel from the emitter to the collector. This is achieved by varying the conductivity of the base region, which, in turn, is made possible by altering the concentration of the impurity atoms in the base material. See figure 2.

The base material of diffused-base transistors is doped so that there is a strong concentration of impurity atoms near the emitter junction and a gradual decrease of impurity atoms toward the collector. This is shown in the figure by the number of vertical lines within the base. Thus, the portion of the base nearest the emitter is a high-conductivity region whereas the area near the collector is a low-conductivity area.

The overall effect is to create a field which sweeps the carriers, moving from the emitter into the base, toward the collector. This reduces the time it would otherwise take for the carriers to cross the base region. A short transit time, reduced to one-fourth or less the normal value, means that the transistor is capable of amplification at considerably higher frequencies. Transistors of this type have been built with cutoff frequencies in excess of 200 mc.

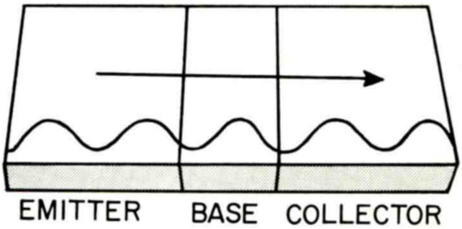
In addition to the improvement in transit time, the high frequency performance of diffused-base transistors is further improved by a reduction in input resistance. With a higher concentration of impurities near the emitter, the input resistance is also less and allows for higher gain. Also, low conductivity in the base area near the collector means that the effective capacitance at the output junction is less (there is less voltage drop at the junction).

These conditions all help to improve the ability of the transistor to provide gain, and most high-frequency transistors now in use utilize some form of impurity gradient in the base. Transistors of this general construction are classed as "diffused-base" transistors.

Surface-Barrier Transistors

Another transistor designed for high-frequency operation is the surface-barrier type. Constructed in somewhat the same manner as the alloy junction unit, the surface barrier gains its high-frequency capabilities from its small size. See figure 3.

Rather than alloying small beads of impurity metal into the base material, surface-barrier transistors are made by electrochemically etching two wells into opposite sides of the base material. These wells are then plated with a material which forms the emitter and collector. This process can be controlled so that the thickness of the base between the emitter and collector is but a few tenths of a mil. This means a very small transit time and good high-frequency characteristics.



Where the Transit Time of the Carriers Through the Base is an Appreciable Portion of One Cycle, the Transistor Will Not Provide Much Gain.

Units of this type have been made with cutoff frequencies around 100 mc.

In more recent developments, the microetching techniques used in the making of surface-barrier units have been applied to the diffused-base transistor, producing microalloy diffused transistors (m.a.d.t.) capable of amplification and operation at vhf frequencies.

Tetrode Transistors

As indicated by its name, we may anticipate that the tetrode transistor has an additional terminal other than the usual emitter, base and collector. Although there are only three active elements in the tetrode, another connection is made to the base, on the side opposite the normal base connection, and a bias voltage is applied between these base connections. See the sketch in figure 4.

The bias voltages applied to the emitter and collector in respect to the base are the same for triode units we have been discussing, but another DC voltage is applied to the transistor base, between the newly-added terminal and the regular base terminal. The extra biasing voltage across the base connections is normally of the same polarity but larger than that applied to the emitter.

An NPN tetrode is shown, and for this unit the voltage to the fourth terminal must be negative. This means that an electric field is established across the base material as a result of this additional voltage, and the field causes the electrons (the carriers moving into the base from the emitter) to follow a narrow, restricted path through the base region as shown in figure 4.

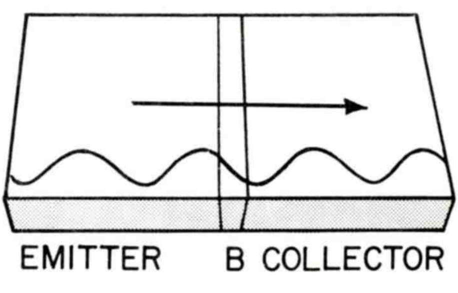
As a result of the narrowed current path, the high-frequency capabilities of the tetrode is improved over the conventional triode. This is due to two factors. First, with a narrower current path the effective capacitance at both the input and output are reduced, allowing for high-frequency operation. Second, the input resistance is reduced because of the shorter path of the emitter-base current. Due to the limited path for current, the power capability of the tetrode is poor; however, this is of no consequence for the requirements of most high-frequency circuits.

Tetrodes in use today are NPN units of the grown type. The two symbols which represent tetrode transistors are shown in figure 4. The upper symbol is the one most often used.

"Mesa" Transistors

An entirely new approach to transistor design has been found. Due to their construction, these units have been labeled "Mesa" transistors; the word "mesa" comes from the Spanish and means "table," and this designation can be understood from the construction of the transistor. See figure 5.

The base is a diffused N region, with an alloyed gold contact. The emitter contact is made by evaporation and alloying, which provides for close control of the important parameters even under mass-production procedures. The collector area is large and has a collector junction which is made from germanium without the presence of any alloy.



A Narrow Base Area Means a Short Transit Time and the Ability to Amplify at Higher Frequencies.

There are many factors which makes this transistor useful at high frequencies. The input resistance of the Mesa transistor is very low and provides a high power gain, particularly at higher frequencies.

The spacing of the emitter and collector is also kept to a minimum and is readily controlled. This also enhances the high-frequency operation. The diffused base reduces the transit time in the base region and also lowers the effective output capacitance. In addition, the features of the mesa transistor indicate that it may be capable of both high-frequency and high-power applications.

At the start, almost all the mesa transistors produced were used by the military and other government services, but units have since been released and are in use in two-way radio communications equipment.

We have just seen the construction of those transistors which seem to be the best suited for two-way communications equipment. Thus far two major advances have occurred as far as transistorized receivers are concerned. The first occurred some time ago when transistorized 455-kc IF amplifiers became possible. This allowed for the major portion of the receiver to use transistors, with only the RF, oscillators and first IF section using vacuum tubes.

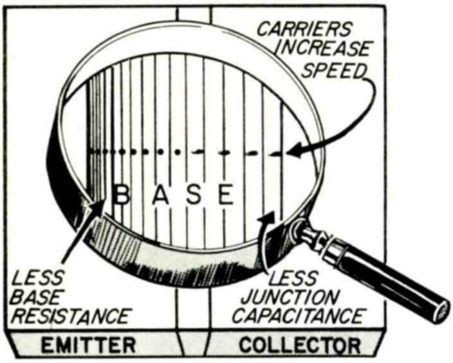
The Handie-Talkie radiophone was the first application of this type, and the basic unit is still in use. In addition to its service as a light portable unit, this receiver has been modified and adapted to provide a low-drain unit for motorcycles and similar vehicles.

The second and equally important break-through in transistor design was the introduction of VHF transistors which could be incorporated into mass-produced, mobile two-way radios. All the stages of the receiver could now be transistorized; this does away with the high-voltage supply, for all the stages operate from the low-voltage primary source. In addition, there are no tube filaments to heat, so that both the standby and the operating currents for the receiver are very small.

In the remainder of this lesson we shall see the use of transistors in the various receiver circuits. Before we start with the IF and RF sections, however, we shall discuss the various methods of coupling high-frequency stages.

IF and RF Coupling Methods

Coupling in either the IF or RF sections of a receiver must take several basic factors into consideration. First, an impedance match must be provided for the input and output circuits if maximum power gain is to be realized. Second, the selectivity achieved by the tuned circuits must be in conformity with the requirements of the receiver at that point.



DIFFUSED BASE TRANSISTOR

The Diffused-Base Technique is Used Almost Universally in High-Frequency Transistors.

For example, a tuned coupling section may provide too little selectivity, in which case undesired signals get through the receiver along with the desired. Or, it may be too selective, in which case the side-band energy of the desired signal does not reach the detector. Thus, it is important to consider the selectivity of tuned coupling circuits as well as the impedances.

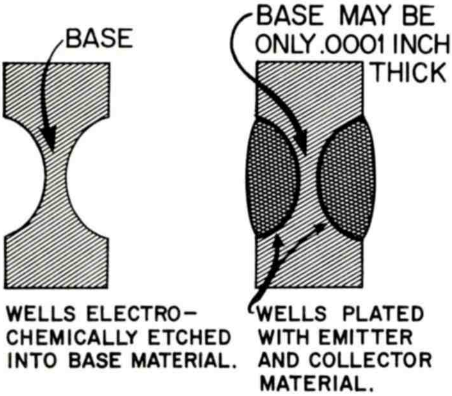
Transistors are quite different from vacuum tubes in the amount of impedance presented at both their input and output. While the output impedance of a transistor may be several thousand ohms for some applications, at high frequencies it will probably be considerably lower. The input impedance to a transistor stage is considerably less than its vacuum-tube counterpart, often being lower than 100 ohms.

When we realize that these input and output impedances of the transistor stage load the tuned circuits with which they are associated, we can readily see why a tuned circuit arrangement which provides a satisfactory amount of selectivity for a vacuum tube stage may not be at all useful for the transistorized amplifier.

When considering coupling systems for transistor stages, it is normal to expect that the input to the coupling element has a higher impedance than the output. This is another way of saying that the output impedance of the transistor stage is normally higher than the input of the next stage. With these factors in mind we are ready to inspect some tuned coupling circuits.

In figure 6 we see a transformer with a tuned primary and an untuned secondary. With the primary circuit tuned and with a relatively few turns in the secondary winding, the primary impedance will be considerably higher than that of the secondary. The secondary is close-coupled to the primary, so that in effect the secondary acts like a tap on the primary, as in figure 7. This, then, is one possible method of coupling from the output of one amplifier stage to the input of another.

Figure 7 shows another means of coupling transistor stages with one tuned circuit. Here a tap on the coil of the tuned circuit provides a point of low impedance, and this tap may be the input to the second stage as shown. In order to prevent interaction of the DC bias voltages, a series DC blocking capacitor is included.



SURFACE BARRIER TRANSISTOR

The Surface-Barrier Transistor is a Means of Securing an Extremely Thin Base Region.

At high frequencies where the coil has but a few turns, it is sometimes difficult to secure the desired impedance at the tap, for the impedance of the tap varies with the "square" of the turns rather than directly with the turns. In addition, where the coil is the tuning element, changing the position of the tuning slug in the coil changes the relative impedances, and thus the impedance ratio. This disrupts the impedance match between the stages.

In figure 8, we see an alternate method of providing the desired impedances with one tuned circuit. Instead of a tap on the coil, two capacitors are placed in series with each other to form the "C" of the tuned circuit, and the "tap" is the midpoint of the capacitors. The impedance of this tap varies according to the reactance of the capacitors, and this is controlled directly by the capacitance of the individual units. Furthermore, the coil may now be tuned without upsetting the impedance ratio of the circuit. The series-connected, DC-blocking capacitor of figure 7 is not needed for this arrangement.

The preceding examples of coupling with but one tuned circuit assume that the loading of the output of the stage upon the tuned circuit does not lower the Q so much as to prevent the desired selectivity. Where the output of a transistor cannot be connected directly to the top of the tuned circuit because of this loading effect, it is permissible to use a tap on the tuned circuit the same as is done for the secondary. See figure 9.

In figure 9 both the input and output connections are provided by taps on the coil. It is possible that either or both of these could be secured by the two capacitors as shown in figure 8.

Combinations of the coupling methods already discussed may also be used. For example, the primary could be connected to a tap on a tuned circuit, with a low-impedance, untuned secondary leading to the input of the next stage. Other combinations are also possible.

Where the required selectivity is greater than can be realized by one tuned circuit, a transformer with both the primary and secondary tuned to the desired frequency may be necessary. Furthermore, the degree of coupling between the two circuits can be adjusted to give the necessary selectivity, see figure 10.

Although many broadcast receivers and other low-frequency equipment make use of inductively-coupled transformer (shown in figure 11A), in high-frequency receivers it is common to find the individual tuned circuits capacitively coupled, (shown in figure 11B). At high frequencies the degree of coupling can be readily controlled by capacitive coupling, particularly where more than two tuned circuits are used.[1]

The 455-KC Amplifier

Having discussed various possible coupling methods for IF and RF stages, we are ready to look at some specific examples. Because it was the first to be used in two-way communications, we shall start with the low-IF section of the Handie-Talkie.

Figure 12 shows the simplified IF amplifier circuit using a PNP transistor in a common-emitter circuit. The positive terminal of a 4-volt supply is grounded, so the emitter is effectively connected to the positive side of the supply. The forward bias on the emitter junction is provided by the voltage divider (R1 and R2), the voltage across R2 making the base negative with respect to ground (emitter).

As soon as the transistor conducts, the voltage drop across R3 makes the emitter also negative with respect to ground. Since both the base and emitter are negative, the forward bias is the difference between the two potentials, or 0.2 volt. The reverse bias of the collector junction is 3.3 volts, the difference between the negative potentials of the collector and base.

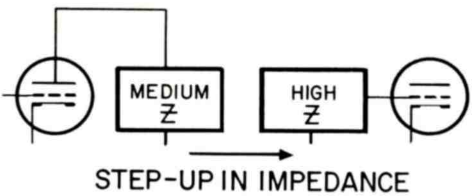
DC stability for temperature changes is provided by resistor R3 in the emitter circuit. The operation of this circuit has been analyzed in preceding lessons. The bypass capacitor parallel to R3 prevents degeneration.

In figure 12, the output is coupled to the next stage by means of a coupling capacitor. This capacitor is in series with the input impedance (capacitance) of the next stage and together they form part of the tuned circuit, for, as far as AC is concerned, they are in parallel with the tuning coil. The coupling capacitor is considerably smaller than the input capacitance of the next stage, so its impedance is high compared with the impedance of the input. This circuit is thus similar to the arrangement of figure 8.

1. See Basic Theory and Application of Transistors (TM11-690), pages 144-151.

Neutralizing the IF Amplifier

Due to regeneration in the 455-kc amplifier, it is often necessary to include neutralization for stable, high-gain amplification. Any system of neutralization which can be used with vacuum tubes applies equally well to transistor amplifiers. Figure 13 illustrates the neutralization system of the IF circuit of the Handie-Talkie. Figure 13A shows the path of the undesirable feedback voltage, from the output through the transistor to the input circuit. In a transistor, this feedback is considerable and it must be counteracted.



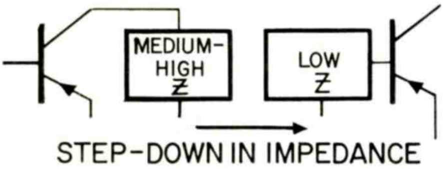
Inter-Stage Coupling Methods in Vacuum-Tube Equipment Must Provide an Impedance Step-Up From One Stage to the Next.

Figure 13B shows the method of securing a neutralizing voltage from the output. When applied back to the input, this additional voltage opposes the internal feedback voltage so that the only effective voltage at the input is the original signal from the preceding stage.

The tuned circuit in figure 13B is "tapped" so that the bottom of the tank is no longer at ground potential. Instead, the tap places the ground at some point between the two ends of the coil. With the ground as reference, the upper and lower ends of the coil (points A and B respectively) are now 180° out of phase with each other.

Point A is the source of the feedback voltage through the transistor; point B is the source of the neutralizing voltage, which is fed to the input through neutralizing capacitor Cn. Since the two voltages reaching the input from the output are 180° out of phase, they will completely cancel each other as far as the input circuit is concerned if they are of equal amplitude; the only effective voltage at the input is that applied from the preceding stage.

In figure 13B the coil is grounded, making it impossible to apply the DC voltage to the collector through the coil. This problem is solved by the alternate system shown in figure 13C. Here the tuned circuit is grounded at the midpoint of two series-connected capacitors. Grounding this point does not affect the DC through the coil. At the same time, a ground point is established for the tuned circuit. The relative position of this tap depends upon the reactances of the two capacitors. The opposite ends of the tank, points A and B, are still 180° out of phase and they become the source of the two voltages fed to the input.



Inter-Stage Coupling Methods in Transistorized Equipment Usually Encounter an Impedance Step-Down to the Second Stage.

Figure 14 shows the complete circuit of the IF amplifier stage. C_O is not an individual circuit component or part, but represents the output capacitance of the transistor and circuit. As far as AC is concerned, the reactance of C1 is so small that we should think of C_O as being connected directly between the collector and ground.

The tap on the tuned circuit, required to establish a neutralizing voltage, is provided by the ground connection between C1 and C2. Considering C1 to be a short as far as AC is concerned, the output circuit is thus the same as figure 13C.

Feedback voltage from the output at point A is conducted through the transistor, represented by the feedback path, C_{FB}. This path is not purely capacitive. Instead, there is a resistive component, so that the feedback sees an internal "RC" path from the output to the input. To maintain the correct phase relationship of the neutralizing voltage, a resistor (Rn) and capacitor (Cn) are placed in the neutralizing circuit between point B and the input. The neutralizing voltage and the feedback voltage are thus maintained at equal amplitude and opposite phase.

Resistor R4 in the supply line has several functions. Together with C2, it acts as a decoupling device, preventing IF currents within the amplifier from appearing on the supply line and interacting with the other IF stages. It also allows the lower end of the tank (B) to be above RF ground potential. Without this resistor, the large capacitor at the power supply would place the bottom of the tank at ground potential as far as the IF is concerned, and point B could not be used as a source of neutralizing voltage.[2]

Another 455-KC Amplifier

Figure 15 shows the circuit of a 455-kc amplifier stage utilized in a completely transistorized mobile receiver. The main differences between this circuit and figure 14 are the transistor used, the coupling system and the neutralizing circuit.

Before discussing each of these factors, let's look at the biasing arrangement. With the negative side of the supply grounded, the collector of the PNP transistor returns to ground through the tuned circuit and the emitter connects to the positive side of the supply through stabilizing resistor R3. This resistor is bypassed to avoid

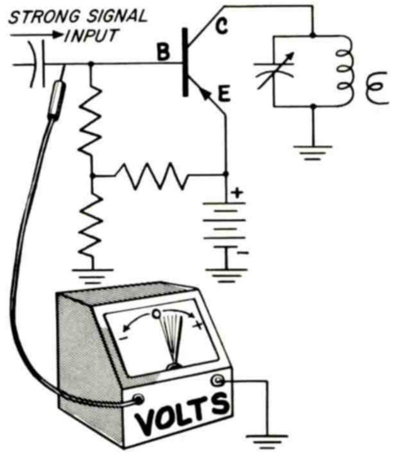
2. See TM11-690, pages 151-155.

degeneration. Resistors R1 and R2 form a voltage divider which establishes the proper bias at the emitter junction.

Figure 15 utilizes a 2N247 transistor, a diffused-base type capable of giving considerable amplification at 455 kc. The collector load is a tuned circuit, with a low-impedance secondary winding providing for the low-impedance input to the following stage. The voltage across this secondary winding is out of phase with the primary voltage and thus provides a convenient source of a neutralizing voltage. Neutralizing capacitor Cn feeds back some of this out-of-phase voltage to the input, thereby counteracting the internal feedback of the transistor. The neutralized stage is capable of providing maximum gain with good stability.

The resistor in parallel with the tuned circuit prevents the circuit from becoming too selective and, as a result, reject the sideband energy of the incoming FM signal. The value of this resistor may be changed according to the required bandwidth of the receiver. A smaller value of resistance provides a greater loading of the circuit and hence a broader response. Large resistance values do not load the tuned circuit so much and allow greater selectivity.

The input to this circuit is the output of the Permakay filter. In the receiver there are two more stages of IF amplification, both with circuits similar to that of figure 15.



When the Input Signal Overdrives the Input Circuit, the Base-To-Ground Voltage of the Transistor Limiter Stage Varies in the Positive Direction.

Untuned 455-KC IF Amplifier

A Motorola VHF pocket-type receiver utilizes several stages of 455-kc amplification which do not incorporate any tuned circuits. The stages are RC coupled and, although more stages are required to provide the necessary gain, the selectivity of this 455-kc section of the receiver is achieved in the Permakay filter and additional selectivity is unnecessary.

One of the major advantages of this procedure is the freedom from any tuning within the 455-kc IF amplifier section; this greatly simplifies the alignment. Furthermore, with small resistors in place of tuning coils and capacitors, the receiver may be made more compact.

The circuit of the untuned IF amplifier is shown in figure 16. The three resistors form a voltage divider and provide the bias voltages at the transistor elements. The resistor between the collector and base also gives DC stability to the amplifier and, because it allows a degenerative voltage from the output to the input, it also lowers the amplification. The gain is comparatively low and the circuit does not require neutralization.

In the complete circuit of this pocket-size receiver, three stages within the IF section are placed in series as far as their DC currents are concerned, and this lowers the total current requirement of the receiver. The arrangement of the DC path is shown in figure 17. Bypass capacitors prevent interaction of the stages due to the common DC current through them.

12-MC IF Amplifiers

Both the high-band pocket and mobile receivers, discussed in the preceding section about 455-kc amplifiers, incorporate transistors in their first IF section; the IF stages operate at 12 mc in both instances. One of these amplifiers is shown in figure 18.

The input to the amplifier is the output of the first mixer, and a tuned, impedance-matching transformer is used between the stages. A high degree of selectivity is desired at this point; it is important to select the desired frequency at the mixer output and to reject the others. The output of the amplifier stage incorporates two tuned circuits which are critically coupled, by a capacitor, for maximum gain with good selectivity. The output tuned circuit has a tapped capacitance arrangement to accommodate the low-impedance input to the following stage.

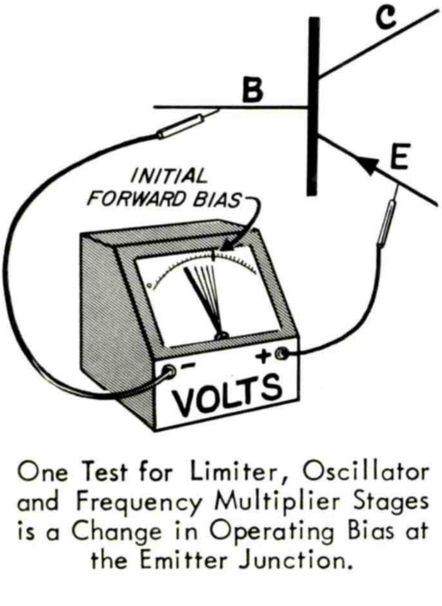
The amplifier stages in the first IF section of this and other Motorola communications receivers are required to furnish a considerable amount of selectivity. This is particularly true when we compare the almost complete lack of selectivity associated with the low-frequency IF amplifier stages. The Permakay filter preceding the 455-kc amplifiers makes it unnecessary to have very much selectivity at this point of the receiver, but the situation at the first IF level is considerably different.

At the first IF section, it is paramount to realize all the selectivity that is practicable, in order to reject as completely as possible the image frequency and those undesirable signals which produce intermodulation and other forms of interference. This accounts for the double-tuned, critically-coupled circuit in the output of figure 18. A double-tuned circuit would also be desirable at the input to this stage. For the desired amount of selectivity and the signal level at this point of the receiver, however, the insertion loss due to the added components would lower the signal-to-noise ratio (sensitivity) of the receiver.

The bias for this PNP diffused-base transistor is secured by a voltage divider, R1 and R2. By-passed resistor R3 in the emitter return provides for DC stabilization without causing degeneration.

The schematic of another 12-mc IF amplifier is shown in figure 19. This circuit provides a considerable amount of gain, and the selectivity is also good. The circuit is neutralized for maximum stability.

The amplifier utilizes a common-emitter circuit. For the PNP transistor and with the supply voltage having a negative ground, the collector is connected to ground through the primary (P) of transformer T2. The emitter returns to the positive side of the supply through stabilizing resistor RE, and the bypass capacitor prevents degeneration.



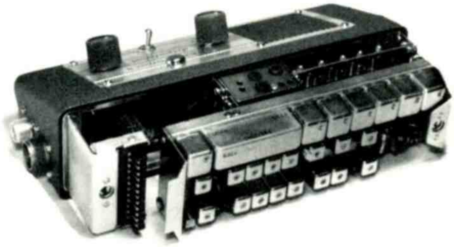
One Test for Limiter, Oscillator and Frequency Multiplier Stages is a Change in Operating Bias at the Emitter Junction.

Forward emitter bias is established by the voltage divider, R1 and R2. A feedback winding on output transformer T2 becomes the source for neutralization voltage, and CN and RN provide the necessary feedback path but limit the neutralizing energy from the output to the input to the desired value.

The input signal to this stage comes from the mixer, and input transformer T1 has three windings. The primary and secondary S (leading to the transistor base) are both low-impedance windings. Selectivity is provided by the third winding, which is tuned to 12 mc.

There are also three windings on output transformer T2. The primary is untuned and has a relatively low impedance. One secondary (FB) provides the feedback voltage for neutralizing the stage, while the other is tuned, providing selectivity. This tuned circuit is critically coupled by a capacitor to another tuned circuit in order to provide additional selectivity. This second tuned circuit is the primary of another transformer T3, and the untuned secondary is the output of the entire stage and is applied to the input of the next 12-mc IF amplifier.

Transistorized RF Amplifier



Here We See The Modular Construction of the Transistorized "Dispatcher" Motorola Receiver.

Two types of transistors are currently being used for RF amplification in high-band Motorola receivers; these are the mesa and the microalloy diffused (m. a. d. t.) transistors. Figure 20 shows a common-base RF amplifier circuit which accommodates either of these transistors, and the PNP transistor symbol is the same for both.

The common-base circuit has a characteristic high output impedance. Thus, it is not necessary to tap the output tuned circuits in order to match the impedances; the design of the tuned circuits is thereby simplified. In addition, the common-base circuit accommodates a larger input signal, an important factor in two-way mobile receiver operation. The gain of the circuit is not so high that the stage is unstable and requires neutralization. Neutralization of a transistor amplifier which must tune over a considerable frequency range is rather complicated.

There is nothing in the circuit which is unusual or different from the arrangements we have just studied. The great difference is in the frequency involved and the ability of the transistor to provide gain at these frequencies. Selectivity is realized by critically-coupled circuits in both the input and output of the stage, and coupling is determined by the value of the coupling capacitance.

Bias is realized by the now familiar voltage divider, R1 and R2, and emitter resistor Re gives DC stability. For this particular circuit the emitter resistor cannot be bypassed, for the signal would then be shorted to ground. The gain is not so great that it is necessary to neutralize the stage.

We have just seen the application of transistors to both the low and high-frequency IF sections and the RF section of the receiver. In the remainder of this lesson we will see other high-frequency uses of the transistor, as limiters and as oscillators.

Transistorized Limiters

The operation of transistors as limiters in the Motorola Handie-Talkie is not much different from their basic operation as 455-kc IF amplifiers. In fact, the only difference between the first limiter stage shown in figure 21 and the

455-kc amplifier of figure 14 is the amplitude of the applied signal.

Operation of the transistorized limiter depends upon the application of a large amplitude signal, the same as the vacuum-tube plate limiter. The collector current of the transistor limiter, like the plate current of the vacuum-tube limiter, is operated between cutoff and maximum (saturation).

We can analyze the operation of the limiters from the circuit of figure 21. With a strong signal applied, the positive alternation of the signal drives the base positive with respect to the emitter; the emitter junction is now reverse biased, and the collector current is zero.

On the negative half of the strong input signal, the base becomes more negative, increasing the emitter-collector current to its maximum value. Once the collector current has reached cutoff and maximum, there can be no further change in the output current regardless of the amount of input.

Thus, by providing a signal of sufficient amplitude to drive the collector current to cutoff and maximum, the transistorized limiter produces an output signal of constant amplitude. However, if the signal amplitude is not sufficient to drive the stage to the limits of collector current, the

This Pocket-Size High-Band Paging Receiver is Completely Transistorized.

circuit operates the same as an IF amplifier. Strong signals hold the plate current as cutoff and saturation during the greater portion of each cycle and thereby provides good noise reduction. This effect is discussed in detail in the lesson dealing with vacuum-tube limiters.

In the transistor circuit of figure 21, limiting is evidenced by a change in the negative voltage between the base and ground--this voltage becomes less negative. The amount of change is determined by the amplitude of the input; for a strong signal the base will actually become positive with respect to the emitter. This change of voltage takes place for a strong noise input as well as for a channel signal.

The change of base voltage becomes a convenient means of determining the relative signal strength, so it is used in alignment. In the receiver, three of the metering points measure limiting; these are in the last limiter, the first limiter and the last IF stages. The last limiter has a positive base voltage with only the front end noise applied. This positive voltage increases with a channel signal, to the point where the first limiter reaches saturation and provides a constant output. When this occurs it is necessary to use one of the preceding meter positions for alignment.

Transistorized Oscillators

Transistorized oscillators are not very different from vacuum tube oscillators; in fact, the basic operation is the same. In order to have self-oscillation there must be (1) an amplifying device and (2) regenerative feedback capable of sustaining oscillation.

Figure 22 illustrates the similarity between the two types of oscillators. At A we see a Colpitts vacuum-tube oscillator, in which the plate-tank capacitor is tapped and a portion of the output energy is fed back to the input. The lower part of the tank (C1) is in parallel with the cathode-ground circuit, with the result that some of the energy in the tank circuit is applied to the grid-cathode circuit.

The polarities show the effect when the plate current increases. The upper end of the tank swings negative to the lower end and the upper end of C1 also becomes negative. This voltage applied to the cathode-grid makes the grid positive (or less negative) and causes a further increase of plate current.

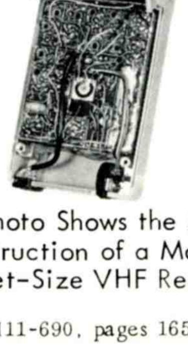
The operation of the transistorized oscillator at B is essentially the same as that of the vacuum-tube oscillator. The tank in the output (collector) circuit is tapped and the emitter resistor is in parallel with C1. Any voltage across C1 is automatically applied between the emitter and base.

The signs indicate the voltage polarity when the current is increasing and the feedback makes the emitter positive to the base. For a PNP transistor this further increases the collector current. During the next half cycle when the current decreases, the feedback voltage has reversed polarity and the forward bias of the transistor is reduced. Thus, the feedback voltage is regenerative and makes the circuit self-oscillating.

Figure 23 shows the arrangement of another vacuum-tube oscillator along with the corresponding transistorized circuit. At A we find a tuned circuit between grid and ground with the cathode connected to the tap. As the plate current increases the cathode current also increases and the cathode swings positive. This voltage is applied to the tap on the tank circuit and, due to the circulating current within the tank and the step-up effect of the tuned circuit, a larger positive voltage appears at the grid. With the grid going positive with respect to the cathode, the plate current tends to increase further--this is feedback in phase and produces oscillation.

The common-emitter transistor circuit at B is very similar to that of A; the tank circuit is between the base and ground and the emitter is connected to the tap. Increasing current through the emitter resistor causes a voltage drop as marked and this voltage applied to C1 in the tuned circuit causes a higher negative voltage at the base; the transistor forward bias is increased. This means an increase in emitter current. The action is regenerative and produces oscillation.

It is interesting to note the similarities in the oscillator circuits of figures 22 and 23. Considering the transistorized versions only, the tank circuit in both instances is between the collector and base and the emitter is connected to the tap. The difference in the figures is only in the point of the circuit which is designated as ground.



This Photo Shows the Modular Construction of a Motorola Pocket-Size VHF Receiver.

There are many other oscillator circuits which are found in vacuum tube and transistorized equipment. Regardless of the circuitry, however, they all follow the pattern that some of the output circuit energy is fed back "in phase" to the input and causes oscillation.[3]

Oscillator Emitter-Junction Bias

We have previously discussed the importance of maintaining a constant emitter junction bias for an amplifier, to the point that stabilizing circuits are usually included to keep a steady bias for changes of temperature, etc. This is necessary in amplifiers in order to keep them operating in Class A, in which the stage operates over the linear portion of the curve and the collector current occurs for the complete cycle. This type of operation, however, is not the manner in which the average oscillator operates.

Instead of operating in Class A, it is more likely that the oscillator will be reverse biased at the emitter junction, and collector current occurs for less than a half-cycle of the input (feedback) voltage. This type of operation is known as Class C. Of course, the stage is forward biased initially, for this is necessary to make the transistor conduct. As soon as the circuit starts to oscillate, however, the bias changes.

3. See TM11-690, pages 165-175.

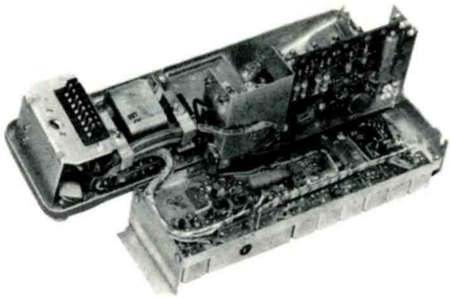
The action of the oscillator bias is the same as that of the limiter stage, which has already been discussed in this lesson. For the oscillator, however, the signal voltage is the feedback from the output to the input. This feedback drives the base further negative than required to cause maximum collector current and, as a result, the base current increases drastically.

This increase in base current causes the base to swing in the positive direction, producing a reverse bias at the junction. In most instances the feedback voltage is sufficient that the stage assumes an appreciable reverse bias; collector current occurs only for a small portion of the cycle, when the base is driven negative by the feedback signal.

The oscillator activity can be readily measured by the change in the base voltage. We will say more about this in the next lesson.

Crystal-Controlled Transistorized Oscillators

A frequency-controlling quartz crystal may be used with the transistorized oscillator just as readily as for the vacuum-tube model. There are two general procedures for inserting a quartz crystal into the oscillator for frequency-control purposes. First, it may be placed in the feedback path so that the only time feedback is established is when the frequency of feedback energy coincides with the natural series-resonant frequency of the



This Photo Shows the Complete Internal Construction of the Motorola Handie-Talkie Transmitter and Receiver.

crystal. The second method is to use the crystal as part of the tuned tank circuit. We shall inspect each of these briefly.

The oscillator circuit of figure 24A is the same as that of figure 22B, when the base is at ground potential. Thus, if the crystal has a low impedance so that the base is effectively at RF ground potential, the circuit oscillates in the manner already described.

The only time that the crystal looks like a low impedance is when the currents coincide with the natural resonant frequency of the crystal. The crystal is then series resonant and has a very low impedance; the crystal has a very high impedance to all other frequencies. A high impedance prevents any appreciable RF change of the emitter-base current and the circuit cannot oscillate.

In figure 24B the crystal functions as part of the parallel resonant circuit (the tuned circuit of the oscillator). The tank voltage has a divider made up of C1 and C2, and the voltage across C1 is fed back to the emitter and produces oscillation. This circuit is again electrically the same as figure 24B. The only difference is the use of the crystal as part of the tank circuit.

Here We See a Battery Supply for a Portable Two-Way Radio.

12-MC Oscillator

Figure 25 shows the low-frequency oscillator of one of Motorola's completely transistorized receivers. The frequency, in the 12-mc range, is determined mainly by the resonant frequency of the crystal.

Coupling capacitor (C) and the load (R) are in parallel with the collector coil (L).

The load has a low impedance, so in effect the capacitor is in parallel with the coil. If we omit the DC biasing components, the circuit simplifies to that shown in figure 25B. Assuming that the circuit is capacitive between the collector and ground--and it is so designed--the circuit is the same as that of figure 24B. Coil L is a means of completing the DC path for collector current without introducing a resistor, which always causes a power loss and poor efficiency.[4]

Transistorized High-Frequency Oscillator

Figure 26 shows the basic circuit of a transistorized, crystal-controlled, high-frequency oscillator used in a high-band mobile receiver. The operating range of the oscillator is around 28-32 mc and this signal is multiplied to the fifth harmonic, producing an output to the mixer between 140 and 160 mc.

The oscillator circuit is essentially the same as that of figure 24A. The emitter is connected to a capacitive tap on the tuned circuit and the output of the oscillator is taken from this same low-impedance point. The crystal in the base return circuit acts like a series-resonant circuit and because of its low reactance at its resonant frequency it allows the circuit to oscillate at this rate.

The resistor parallel to the collector tuned circuit broadens the response of the circuit. This allows for the collector circuit to be tuned with but a minimum effect upon the oscillator frequency. The oscillator frequency is controlled by the variable capacitor in series with the crystal. Varying the

4. See TM11-690, pages 175-177.

amount of reactance in the crystal current path causes a change in frequency, the same as was accomplished for vacuum-tube receivers.

Frequency Multiplier

We found, in our study of crystal-controlled oscillators for high-band receivers, that oscillators at the mixer injection frequency are not practicable; instead, a low-frequency oscillator is used, followed by a frequency multiplier. The output circuit of the multiplier is tuned to a harmonic of the input signal, thereby making that harmonic frequency available for injection at the mixer.

Figure 27 shows a typical multiplier circuit, which follows the high-frequency oscillator in a high-band transistorized receiver. This circuit operates at the fifth harmonic of the oscillator frequency. By operating the stage in Class C and tuning the collector circuit to the desired harmonic frequency, the output frequency is five times higher than the oscillator frequency.

Class C operation is established by having a strong signal at the input (base), thereby driving the stage beyond the normal range of collector current. Again the same action takes place as was discussed for the limiter and oscillator stages, in that the base current increases considerably and reverse biases the emitter-base junction.

Collector current occurs as short pulses, each lasting for a very small part of the complete cycle of input signal. The collector load consists of three high-Q, critically-coupled circuits tuned to the fifth harmonic of the input signal. Because of the selectivity of the tuned circuits, all frequencies except the fifth harmonic are attenuated and only the desired signal reaches the mixer with appreciable amplitude. The output tuned circuit is tapped to provide the low-impedance input to the mixer.

Discriminators

Discriminators and other forms of FM detectors require two diodes. It does not matter whether these are vacuum-tube diodes or semiconductor diodes, for the circuit operation remains the same.

If semiconductor diodes are used, they should have a good front-to-back resistance and conduction ratio. That is, the conduction should be good in one direction, but the resistance in the other direction should be very high. In addition, a diode capable of operating at higher temperatures without changing conduction characteristics is important, for in two-way equipment the operating temperature is often at the extremes of heat and cold. Thus, silicon diodes are the most satisfactory.

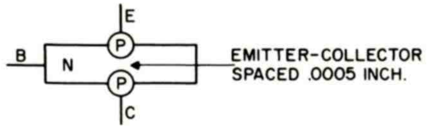
The operation of the circuit remains the same regardless of the type of diode used. Discriminator operation is described in complete detail in an early lesson, in the receiver section of this training.

This concludes our discussion about the use of transistors in high-frequency applications. The next assignment is devoted to the subject of servicing transistorized equipment.

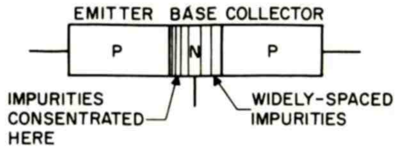
STUDENT NOTES

STUDENT NOTES

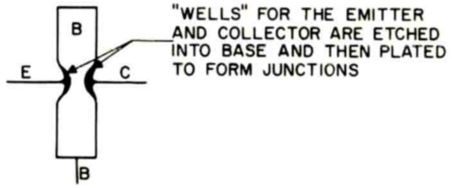
STUDENT NOTES



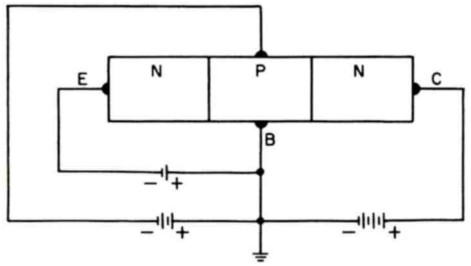
ALLOY JUNCTION TRANSISTOR
FIGURE 1



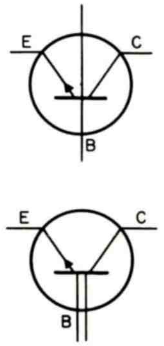
DIFFUSED-BASE TRANSISTOR
FIGURE 2



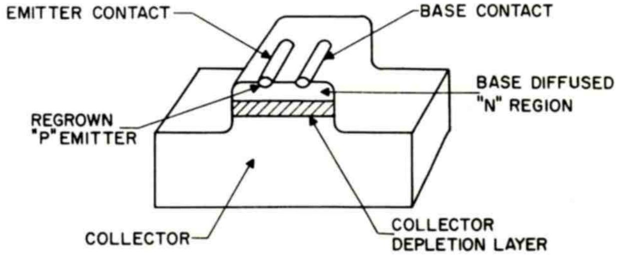
SURFACE-BARRIER TRANSISTOR
FIGURE 3



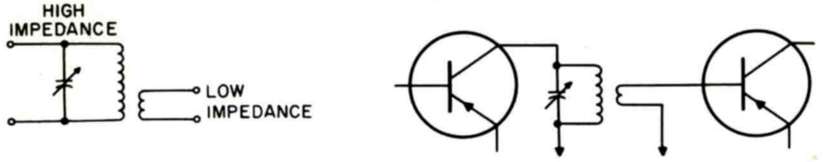
TETRODE TRANSISTOR
FIGURE 4



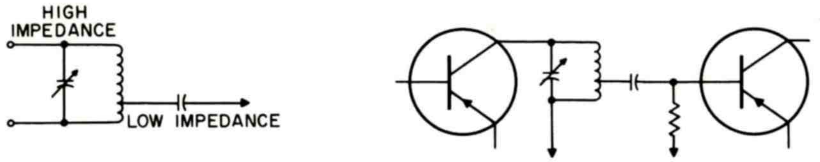
NPN/TETRODE
SYMBOLS



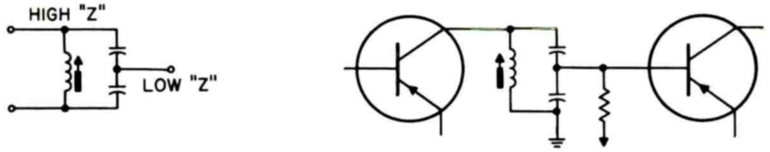
MESA TRANSISTOR
FIGURE 5



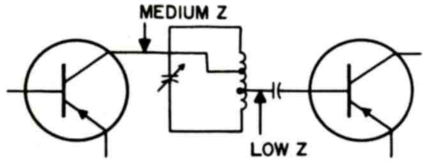
TRANSFORMER COUPLING
FIGURE 6



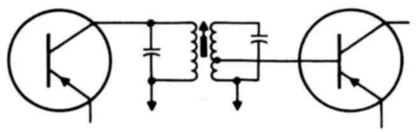
"TAPPED" COIL COUPLING
FIGURE 7



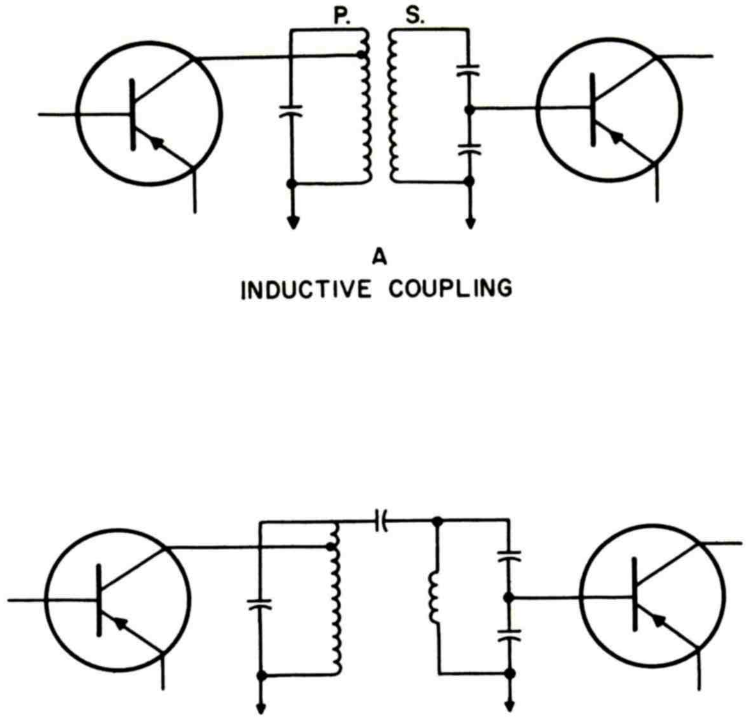
"TAPPED" CAPACITOR COUPLING
FIGURE 8



"DOUBLE-TAPPED" COIL
FIGURE 9



"TAPPED" SECONDARY
FIGURE 10



A
INDUCTIVE COUPLING

B
CAPACITANCE COUPLING

FIGURE 11

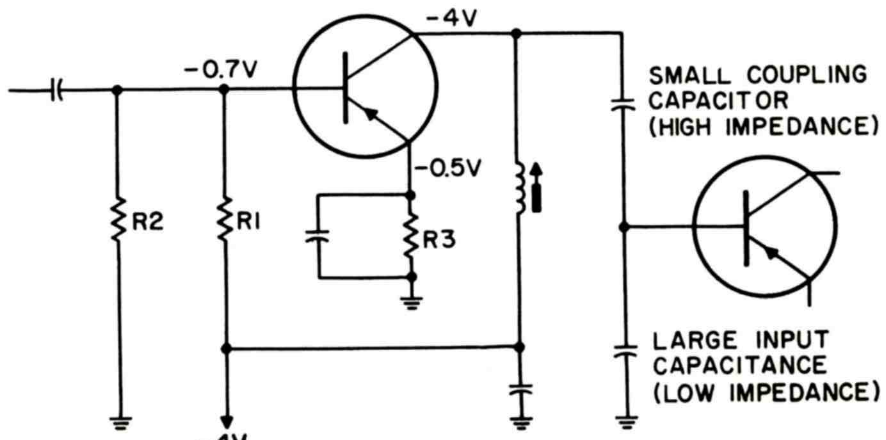
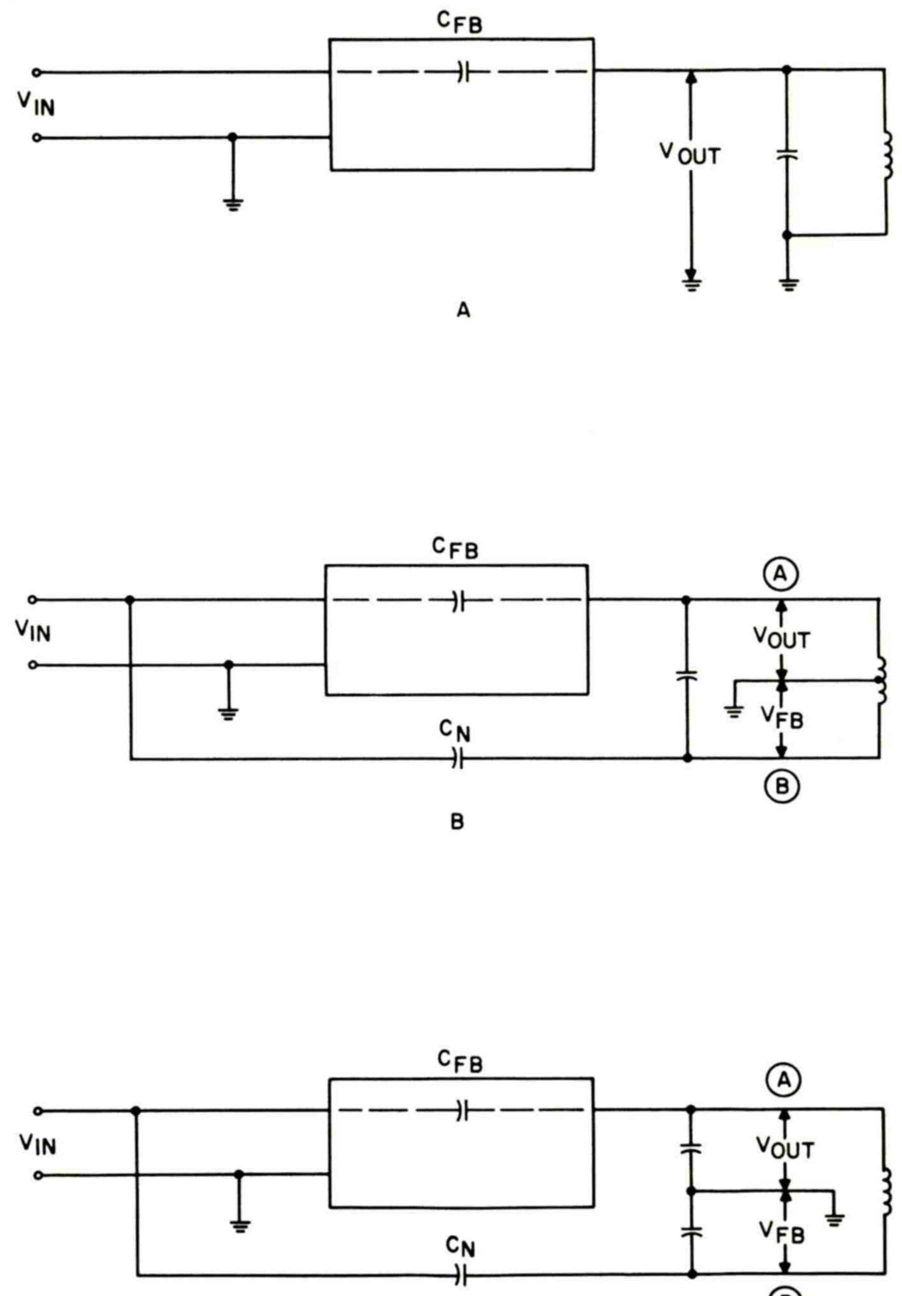
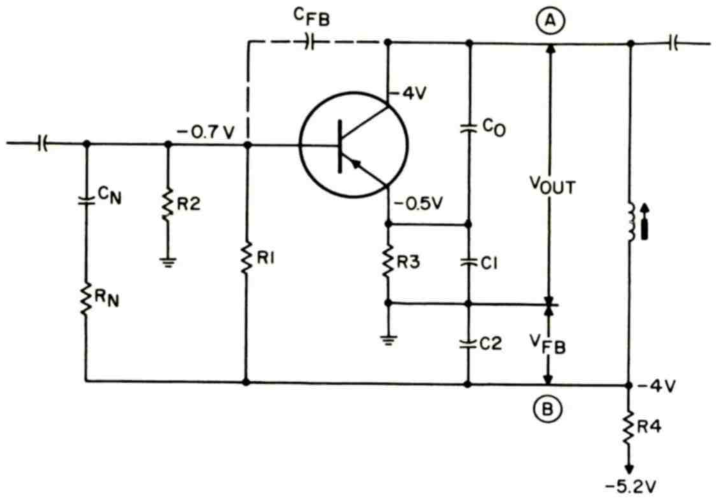


FIGURE 12



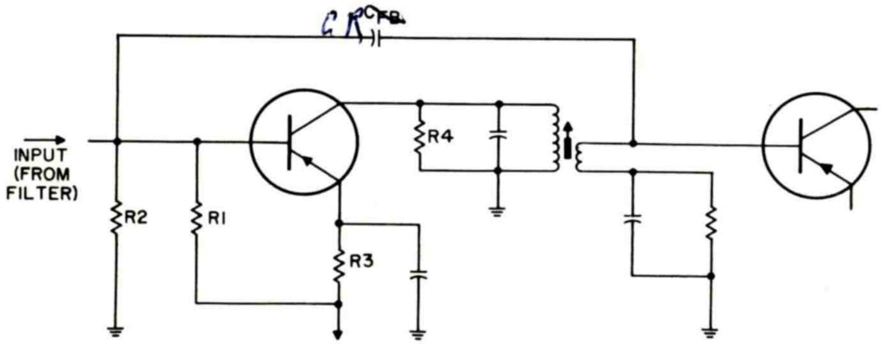
NEUTRALIZATION

FIGURE 13



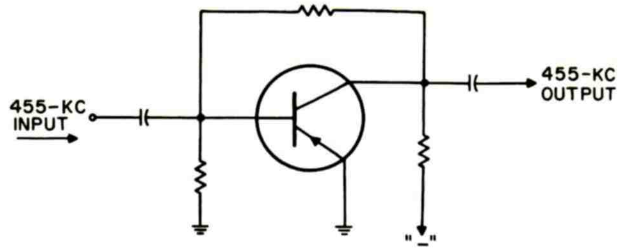
455-KC IF AMPLIFIER

FIGURE 14

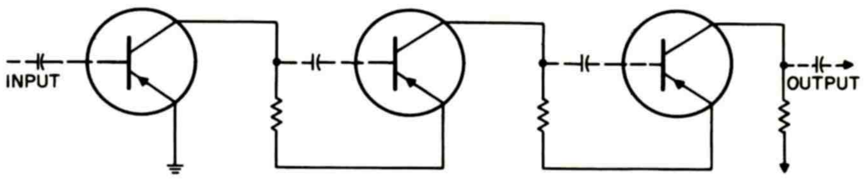


455-KC IF AMPLIFIER

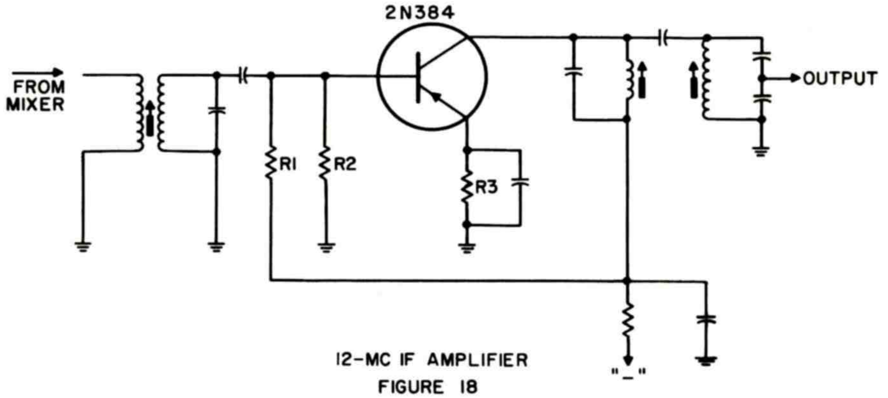
FIGURE 15



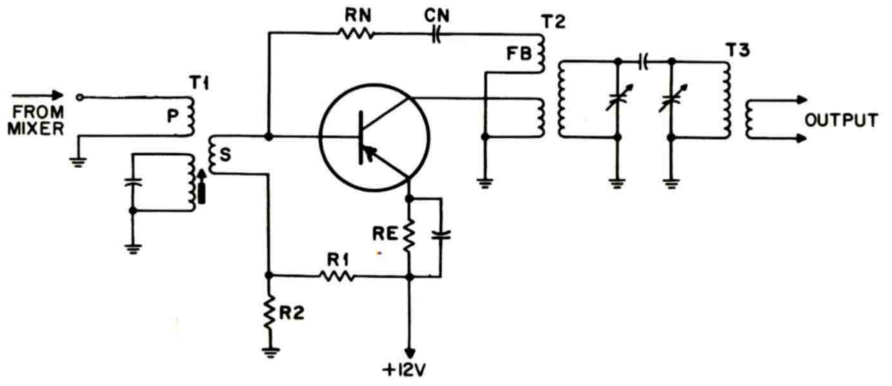
UNTUNED IF AMPLIFIER
FIGURE 16



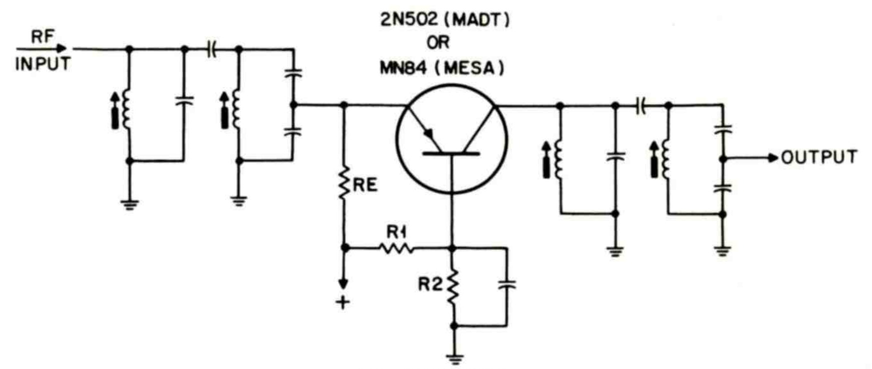
DC SERIES-CONNECTED STAGES
FIGURE 17



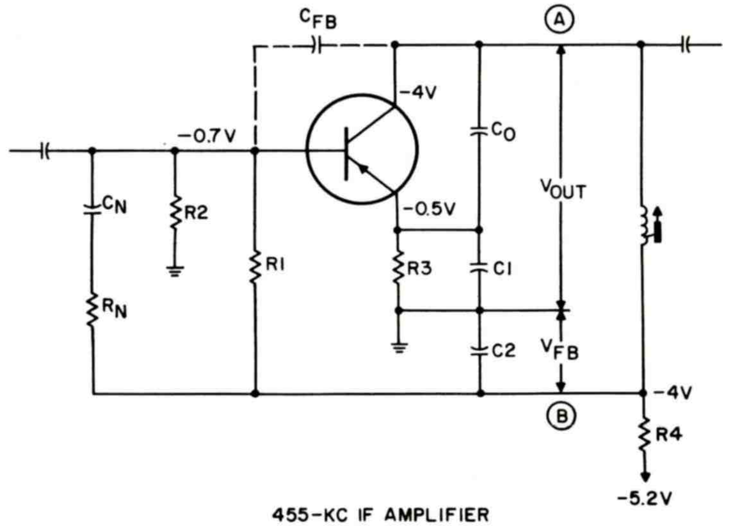
12-MC IF AMPLIFIER
FIGURE 18



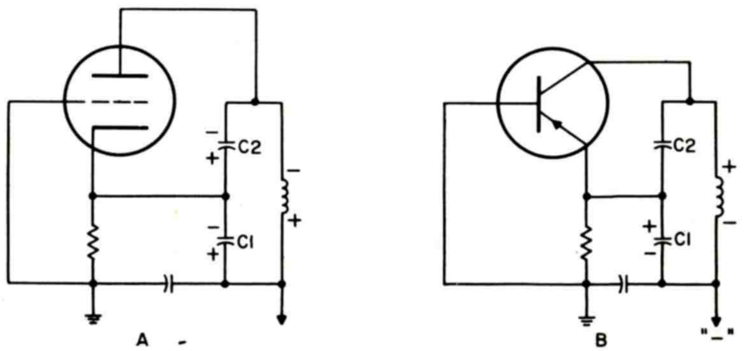
12-MC IF AMPLIFIER
FIGURE 19



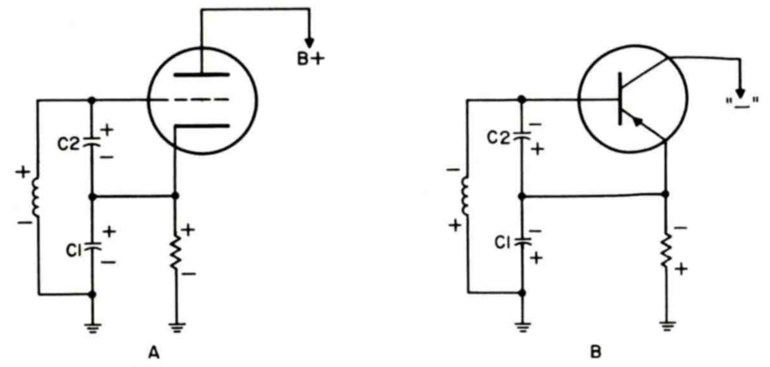
RF AMPLIFIER
FIGURE 20



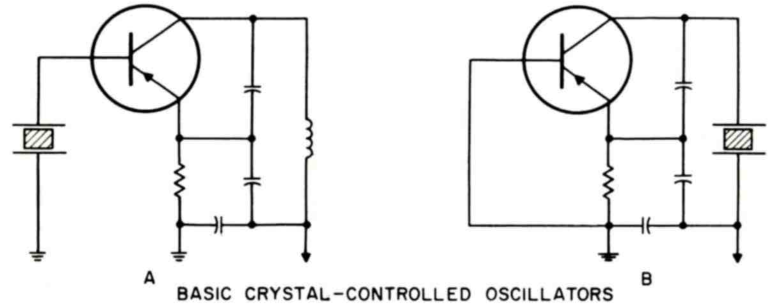
455-KC IF AMPLIFIER
FIGURE 21



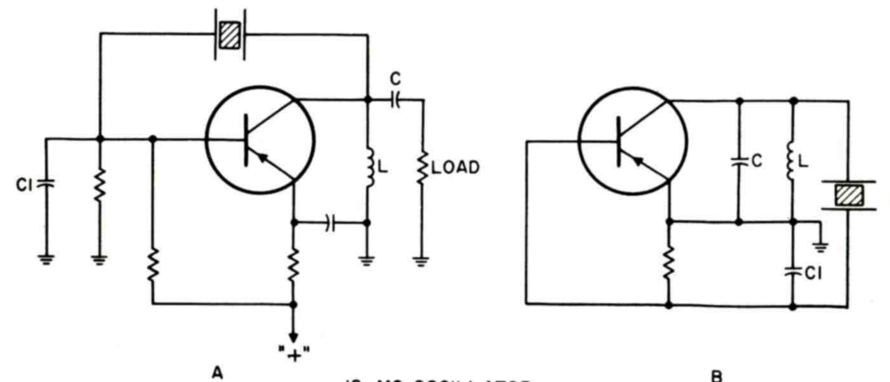
BASIC OSCILLATORS
FIGURE 22



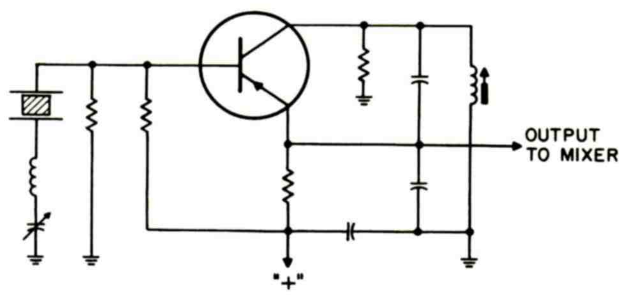
BASIC OSCILLATORS
FIGURE 23



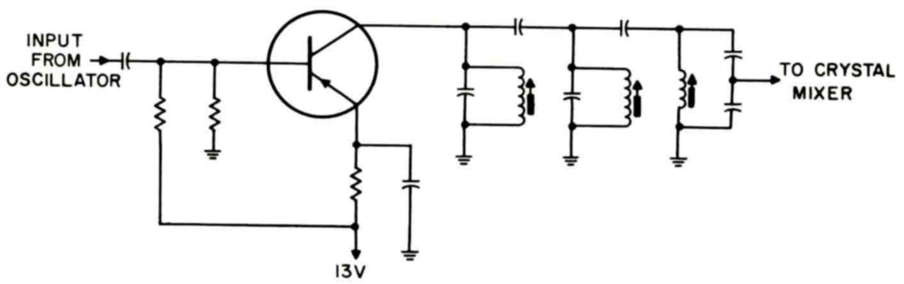
BASIC CRYSTAL-CONTROLLED OSCILLATORS
FIGURE 24



12-MC OSCILLATOR
FIGURE 25



HIGH-FREQUENCY OSCILLATOR
FIGURE 26



MULTIPLIER (RECEIVER-OSCILLATOR)
FIGURE 27

national
MOTOROLA
RADIO COMMUNICATIONS
service

A TWO-WAY RADIO COMMUNICATIONS TRAINING PROGRAM

LESSON SA-8
TRANSISTORS

Servicing Transistorized Equipment

MOTOROLA TRAINING INSTITUTE

A TWO-WAY RADIO COMMUNICATIONS TRAINING PROGRAM

LESSON SA-8
TRANSISTORS

Servicing Transistorized Equipment

—one of a series of lessons on two-way FM communications—

MOTOROLA TRAINING INSTITUTE
4501 W. AUGUSTA BLVD., CHICAGO 51, ILLINOIS

APPROVED BY THE STATE OF ILLINOIS
DEPT. OF REGISTRATION AND EDUCATION

PREFACE

This is one lesson of a complete Motorola Home-Study Course which presents to the Service Technician both the principles of operation and the maintenance of two-way FM radio systems. The program covers mobile, portable and base station equipment, including the latest transistorized units.

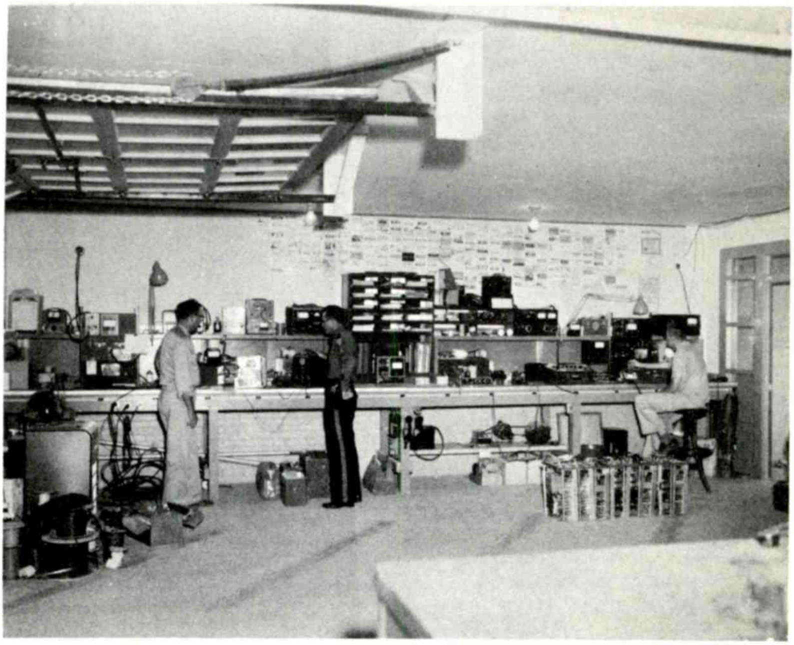
SERVICING TRANSISTORIZED EQUIPMENT

LESSON SA-8

TABLE OF CONTENTS

NOTICE

Diagrams and figures referenced in text are "fold-outs" in back of each lesson, for use while studying. The Examinations are also there.



Adequate bench space and equipment is needed for efficient servicing of mobile radios. Reference literature is also conveniently located. This Maintenance Center accommodates several technicians.

SERVICING TRANSISTORIZED EQUIPMENT

Lesson SA-8

Introduction

When the two-way service technician who has been accustomed to vacuum-tube equipment first encounters completely transistorized units having modular construction, he is likely to get the impression that here is something entirely new and that he must now "start from scratch." This feeling is unchanged when he contemplates the procedures for changing component parts or making voltage and resistance checks within the equipment. This serviceman is in for a pleasant surprise when he starts to troubleshoot the equipment, however, for he now realizes that he uses the same procedures he followed for vacuum-tube equipment. Thus, although the technician must learn some new techniques about working with transistors, he will make good use of what he already knows.

In this lesson we shall be concerned with the service of transistorized power supplies as well as with transistorized receivers. Because these units are considerably different in their operation and are located on different chassis, we shall discuss them separately, starting with the receiver. In our discussions we shall assume that previous lessons dealing with vacuum-tube receiver service and transistor power supplies have already been studied.

Shock Hazard

One of the most notable differences in working with these receivers is the absence of high voltages which constitute a shock hazard. Because all the stages require low voltages and thus operate directly from the vehicle battery, there is no high voltage at the receiver. Voltage measurements and other service procedures may be performed without the usual precautions against contacting high-voltage points.

Under normal conditions the 12-volt supply line to the receiver does not cause any sensation if contacted directly. This does not mean that the serviceman may become careless in his work habits, however, for screwdrivers, test leads and other tools may "slip" and short out a component or circuit and damage the transistors. Transistors are very sensitive to surge currents; vacuum tubes are not.

Another word of precaution is necessary. The serviceman must not become so careless in his working habits as to forget about high voltages when it comes to working on the transmitter or power supply. Or, while working on the receiver, the transmitter may be turned on inadvertently so that high voltages are present in the complete assembly. Although there are no high voltages at the receiver, the serviceman may have his hand or arm laying across a high-voltage point in the transmitter or power supply!

The Shock Hazard Inherent to Tube-Type Receivers is Not Presen in Transistorized Receivers.

Receiver Supply Voltages

The receiver power supply is not considered as an integral part of the receiver. In any trouble-shooting plan, however, we must not overlook the fact that the receiver cannot operate normally if the supply voltage is improper. The problem is less complicated for transistor units, for transistors all operate from one common supply voltage; in contrast, vacuum-tube receivers require a variety of voltages for the tube filaments, screen grids and plates.

It is common to have at least two supply voltages to vacuum-tube receivers, whereas transistorized models require only one supply line. Furthermore, the transistorized mobile receiver operates directly from the primary source; there is no power supply to convert the primary voltage to some other values.

We need make but one voltag check in the receiver to deter mine that the supply is normal an in mobile applications where th battery is capable of delivering large amount of current, the lo drain of the receiver is not likely to cause the battery to "run down" in a short time. For portable units, the power supply consists o a few batteries or a small "powe pack" and is a more likely source of trouble.

In two-way radio equipment receiver failure may be due to drop in the primary power source and it is well to first check tha the supply voltage at the receive is normal. We must not forge hat relays and fuses in the control line may also be a source of rouble.

In the rest of our discussions about receiver service we shall assume that the power source has been checked and found to be normal, so that any trouble must be n the receiver circuits. In addition, we shall assume that the antenna and antenna relay are normal.

Metering Methods

In analyzing vacuum-tube communications receivers, we found that test points in certain circuits were very helpful in localizing a trouble to some stage or portion of the receiver. The same applies to transistor receivers, for again the trouble must be traced to some section or stage before the exact defect can be determined.

Motorola transistorized mobile receivers have the same metering system as the vacuum-tube versions. That is, the various test points are connected to terminals of a socket and when the Motorola Test Set is plugged in, the circuits may be quickly checked by means of the switch (on the test set).

Figure 1 shows the block diagram of the high-band Motorola transistorized receiver, including the various test points. The block diagram is not any different from vacuum-tube models, and this could well be a vacuum-tube type. We can expect to measure the discriminator output in position 4, and the oscillator is measured in position 6, the same as was done in other Motorola receivers. There are some variations from one model receiver to another, however, and the instruction manual will give details concerning any receivers which are new to you.

The manner of providing the readings for transistorized receivers is not always the same as was done for vacuum-tube receivers, but this is of no consequence so long as the reading indicates the operating condition of the receiver at that point. To illustrate the differences in providing readings, for figure 1 the readings of positions 1, 2 and 3 are due to the RF level in the output circuit of the stage, and are secured by placing a rectifier diode and filter in parallel with the output circuit and reading the relative strength of the RF by the amount of rectified DC.

In vacuum-tube models the corresponding metering positions are found in the grid circuits of the tubes and the readings are the result of grid rectification of the signal within the tube. These readings are in reality a measure of the amount of limiting taking place. In either case, however, the readings are a reasonable indication of the amount of RF present at that point of the circuit.

The Motorola pocket-sized, two-way receivers do not have a plug-in arrangement like the mobile units, and for several reasons. First, the small size of the unit does not allow for a plug without requiring a larger chassis and case. Second, the receiver chassis is readily available accessible for testing purposes, so that it is just about as easy to make voltage checks at the color-coded test points with a regular voltmeter as it is to use the test set.

Some of the test points in the pocket-size receiver require the use of an AC voltmeter, and adapters are available which can be used in connection with the Motorola test set.

Localizing the Trouble

The same procedures used in localizing the trouble in the vacuum-tube receiver are followed for the transistorized receiver. Up to the point of determining the specific component which is defective, the serviceman need not be concerned whether the receiver uses vacuum tubes or transistors.

There are four specific procedures which the technician may follow in his efforts to identify the trouble. While these have already been discussed in a preceding lesson about receiver servicing, we shall make a quick review of them here.

1. Operate the receiver controls to determine whether there is noise present and, if there is, how much? Also, if noise is present, does the receiver respond normally to the ad justment of the squelch con trol?

   According to his findings, th serviceman may know jus about where the trouble is an resort to a more detaile scrutiny of the squelch an audio sections with the use o a voltmeter, or he may deen it necessary to employ addi tional procedures to isolat the trouble.

2. Take meter readings, usin either the Motorola test set o a voltmeter, whichever i called for according to th receiver being tested. Thes meter readings yield an over all view of the operation o the front end portion and low IF section of the receiver including the limiters an discriminator.

   If a channel signal is avail able, the readings take o greater value; by observin any changes in the readings we may determine whethe more detailed troubleshooting should be performed in some particular section of the re ceiver, or whether additiona efforts to localize the troubl to some stage are needed.

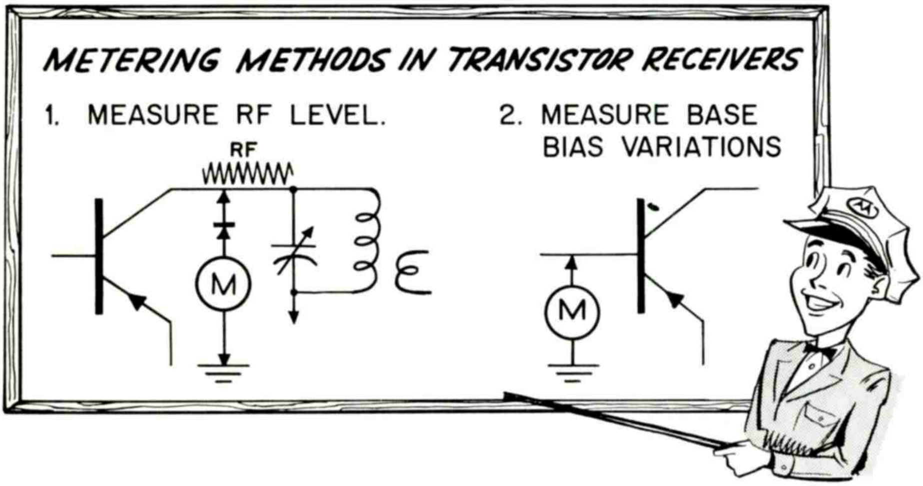
3. Alignment procedures ar helpful in determining the op eration of the tuned stages Where a tuned circuit provide normal changes in the mete readings when adjusted, it i

permissible to temporarily assume that the stage is normal. Failure of a tuned circuit to produce the proper changes in meter readings as the circuit is tuned is often valuable in diagnosing trouble.

4. Another method of determining the stage or section of the receiver giving trouble is to make stage-gain measurements. This procedure may be of more value and used more often with transistorized receivers than with vacuum-tube types, and for two reasons. First, with vacuum tubes it is relatively simple to change a tube and compare results. This is not true of transistors. Second, although vacuum tubes have been the most common source of trouble, transistors are not.

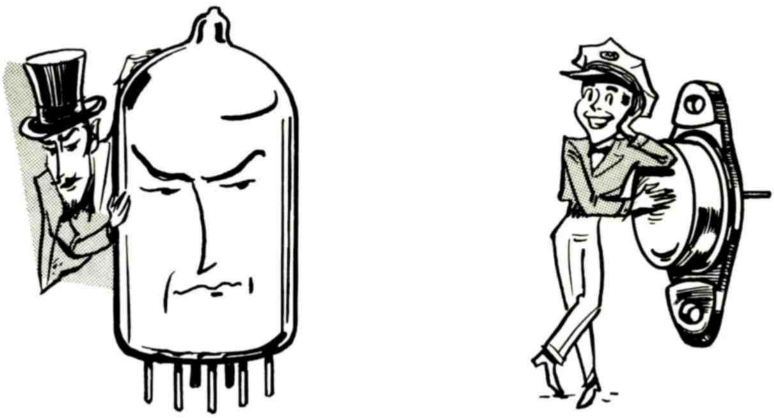
The serviceman will probably make complete checks and be reasonably sure that a transistor is defective before any substitutions are made. This is particularly logical when we consider that transistors are more durable and are not likely to become defective as quickly or as frequently as do vacuum tubes. Thus, it will be best for the serviceman to be reasonably sure of the probable trouble before substitutions are made. More detailed stage-gain measurements will probably be necessary.

The transistor has already lived up to its promise of being a very rugged and nearly trouble-free device. For this reason, it is about the last unit in which we should expect trouble and it is not wise to substitute transistors merely on the assumption that one might be bad.



Either or Both of These Metering Methods May Be Encountered in the Transistorized Communication Receiver.

Transistors are not a major source of trouble in the transistorized receiver and they are often soldered directly into the circuit rather than use sockets. Although this makes it a little more difficult to replace transistors, it insures longer positive contacts to the transistor and avoids one major source of future trouble.



Tubes Have Always Been a Source of Trouble: Transistors Are Nearly Trouble-Free.

Isolating the Fault Within a Stage

After a specific stage has been identified as the cause of the inoperation or poor operation of the receiver, the next step is to determine which specific component within the stage is defective. This may require any or all of the following: voltage measurements, resistance and continuity checks, and a visual inspection.

Although we may suspect the transistor as being the most likely source of the trouble, it is best to know for certain what is at fault before changing parts. A defective transistor will generally show up in voltage checks, for it has been found thus far in working with transistor circuits that the transistor usually becomes "real bad" rather than develop some minor trouble. As a result, there is a notable change of circuit voltages.

All changes of operating voltage are not due to defective transistors, however, for there are other components which cause similar changes in the voltages when they become defective. Thus, in addition to voltage checks, it is almost essential to make resistance and continuity tests of the components. We shall now discuss each of these in greater detail.

Voltmeters

Before making any voltage measurements, it is important to first know what types of voltmeters are permissible to use in transistor circuits. It is generally accepted that any voltmeter is suitable for measuring the voltages of transistor circuits and that it is not necessary to have a vtvm (vacuum-tube voltmeter). Although this is true for most voltage measurements, there are some instances where meters of lower sensitivity produce erroneous and misleading readings.

Meters with low sensitivity of 1000 ohms/volt are not very satisfactory, for when used on their 10-volt scale they have an internal resistance of only 10,000 ohms, and this can change the operation of the circuit considerably when connected in parallel with certain circuit sections.

Meters with 20,000 ohms/volt sensitivity are better, for on their 10-volt range they present an internal resistance of 200,000 ohms. There are not many transistor circuits where this amount of resistance will alter the operation of the circuit to any appreciable amount. The vtvm is still better, for on any DC scale the meter has a resistance of abo[illegible] 11 megohms.

The voltage readings associated with transistor circuits appear to be very low if we are accustomed to vacuum-tube equipment. The two-way radio using tubes usually has a 200-volt supply for the screens and plates. By comparison, the transistorized two-way receiver operates from a 12-14 volt supply, which is less than one-tenth of the other. For this reason we can expect to use the lower scales of the meter. A 0-30 volt scale is suitable for the higher voltages, but there are some values which are less than one volt and require a 3-volt or even a 1-volt range (full-scale deflection).

In taking voltage readings for any electronic equipment it is generally conceded that a 10% variance is permissible. Many of the circuit components have a 10% tolerance, and when several such units are combined into the same circuit, it is surprising that the voltages as a whole stay so close to the average value.

When we consider a 10% variation for a 200 volt supply, or for a 100 volt rating of a screen grid, we are dealing with a 10- or 20-volt variation from the recommended value and still have an acceptable reading. Continuing our comparison, 10% of the voltages found in transistor circuits will be around 1 volt or less. In fact, as we shall see, there are some voltages which must be measured accurately to within "tenths" of a volt in order to determine the actual operation of the circuit.

Summarizing our discussion of voltmeters, we reach the following conclusions:

1. Although other types of meters may be used for most

measurements in transistorized circuits, it is best to use the vtvm in order to assure accurate readings for all circuits which might be encountered.

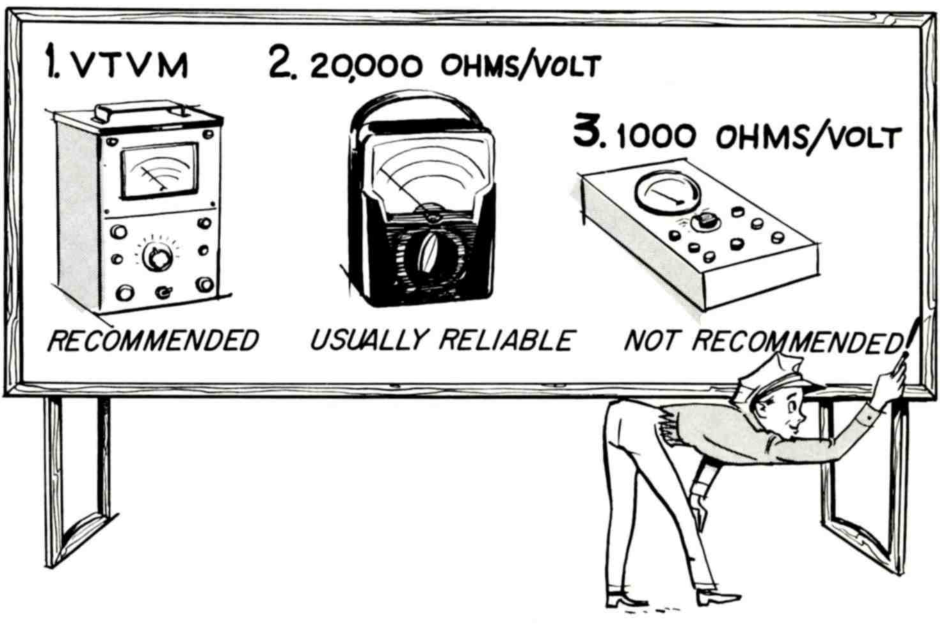
2. Lower voltage scales are required for transistorized equipment, due to the lower supply voltages and the low voltages at the various circuit terminals. The meter should have a range as low as 3 or even 1 volt for full scale deflection.

3. The 10% variation in readings which applies to vacuum-tube equipment also applies to transistorized receivers, but 10% of the relatively low voltages encountered in transistor circuits is usually 1 volt or less.

We are now prepared to proceed with a discussion about those voltage readings in transistor circuits.

Voltage Measurements

In using the meter to measure any voltages associated with transistors (the same also applies to vacuum-tube circuits), we should be aware of any effect the meter might have upon the operation. It is possible for the meter to actually change the operation of the circuit being tested to the extent that the equipment actually becomes inoperative during the test.



Whenever Possible, Use a VTVM; Don't Rely on Less Sensitive Meters.

The proper methods of connecting meters into transistor circuits in order to measure voltages is illustrated by figure 2. Here we see the DC circuit of an RC-coupled amplifier. The capacitors, which have little effect upon the DC voltages, have been omitted for simplicity.

One of the first rules which is well to observe, is not to measure voltages directly between the various elements of the transistor. Although this is permissible in some instances, in others the presence of the test leads will change the operation sufficiently that the readings are not accurate. Instead of measuring between elements, then, it is better to measure the voltage at each element with respect to ground and, from these readings, determine the actual voltage between the elements. Look at figure 2.

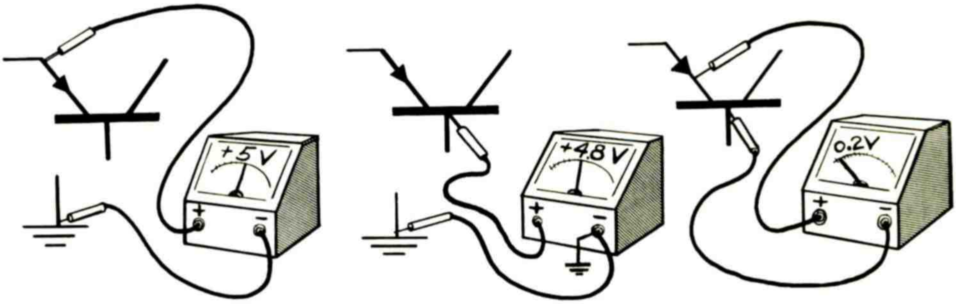
Suppose that we wish to measure the emitter junction bias of the transistor, the voltage between the emitter and base. From the voltages given in the figure, the emitter should be -1 volt to ground and the base -1.2 volt to ground. Because these are both negative voltages with respect to ground, the actual emitter-base voltage will be the difference in these voltages, or 0.2 volt, with the base being negative. Therefore, the emitter junction should be forward biased.

The separate voltages are now measured with a meter. With the positive side of the supply grounded, the voltages of the circuit will all be negative with respect to ground; this means that the positive test lead is connected to ground and the negative lead to whichever point we wish to measure.

In measuring between the emitter and ground, we actually measure the voltage drop across emitter resistor RE. Similarly, in measuring the base-ground voltage, we record the voltage drop of R2. If the voltages are reasonably close to the recommended values we can assume that the stage will be near normal, for the forward bias of the transistor is the major consideration in controlling the operation of the stage.

A check may be made on the drop across collector load resistor RC; with the collector-ground voltage equal to 3.5 volts and with a six-volt supply, the drop across the collector resistor must be the difference in these voltages, or 2.5 volts. (This is in agreement with the basic principle that the sum of the voltage drops about any one circuit must equal the supply voltage.) In a similar manner, if the voltage across R2 is 1.2 volts, the voltage across R1 must be 4.8 volts, for these two resistors are also in series with each other and connected across the supply.

As soon as these voltages have been measured, the operating voltages at the transistor elements can be readily determined. The forward bias of the emitter junction has already been dis-



Do Not Measure Emitter Junction Bias Between the Emitter and Base: Instead, Measure Each with Respect to Ground.

discussed. The reverse collector-base bias is the difference of the voltages of the collector and base, measured with respect to ground; as indicated in figure 2, this is 2.3 volts. The collector-emitter voltage should be 2.5 volts, the difference between the emitter and collector voltages.

There are several additional factors about the forward bias in figure 2 which warrant discussion. The most important is to measure the voltages carefully, for a small error in either the base or the emitter readings with respect to ground may cause a large change in the calculated bias voltage. Let's take an example.

Suppose that the meter reading for the base voltage is actually 1.3 volts, but the serviceman, knowing that the reading should be around 1.2 volts, decides that the reading is okay. "Close enough," he says to himself (the value is within 10% of the correct amount).

Let us assume further that the actual emitter voltage is 0.9 volt. Again the serviceman notes that the value is within 10% of the suggested reading of 1 volt and assumes that everything is normal. Is it, however? NO! The actual bias voltage between the emitter and base is 0.4 volt, twice the desired value of 0.2 volt. Obviously there may be something wrong with the operation of the stage if the forward bias is double what it should be! A further detailed check is indicated.

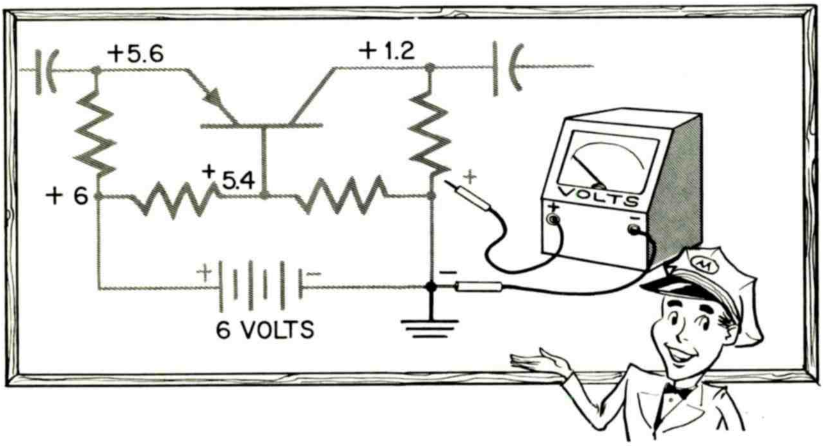
Let's take another example. Assume that the voltages of both the base and emitter are more than 10% from the recommended voltages. However, let these voltages be 1.5 volts and 1.3 volts, respectively. The forward bias is now 0.2 volt, the desired amount. This is normal even though the base and emitter voltages are considerably more than 10% from the quoted value. A further analysis of the voltages of the circuit will probably disclose that the supply voltage is higher than normal, making all the voltages comparatively higher. The circuit is probably performing normally.

In summarizing these two examples, we conclude that considerable intelligence must be exercised in analyzing the readings secured on meters. And, for these examples, we see that a knowledge of transistor operation is essential if we are to properly interpret the readings and determine which variations are acceptable and which mean "trouble." In the first example the individual voltages were actually within 10% of the rated values, but the important voltage, the emitter forward bias, was twice the desired value. In the second example the voltages were all more than 10% from the indicated values, but the forward bias was normal.

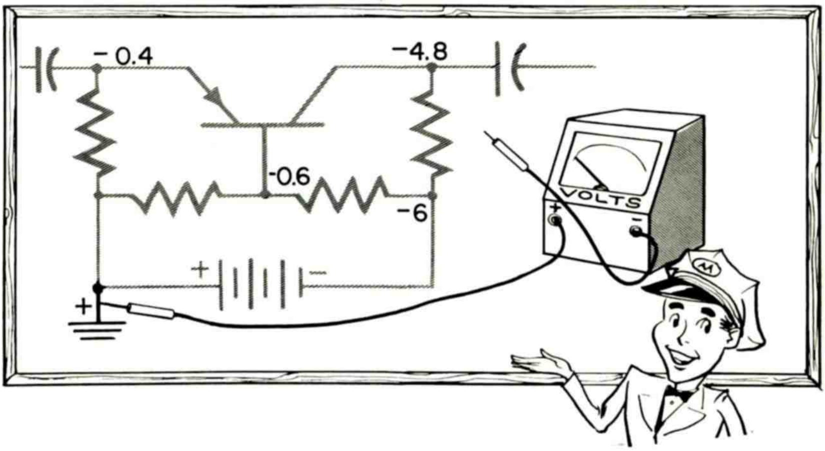
RC-Coupled Amplifier Voltages

Figure 3 gives the complete circuit of figure 2; the bypass and coupling capacitors are included. The voltages at the various circuit terminals are the same. Thus, in making voltage checks in figure 3 we follow the same procedures described for figure 2.

In figure 4 we see a very interesting variation of the circuit of figure 3. With the exception of the negative side of the power supply being grounded instead of the positive side, the circuits are exactly the same. At first glance it appears that the voltages are different, but a careful analysis dis-



When the Negative Side of the Supply is Grounded, Connect the Negative Test Lead of the Voltmeter to Ground and Take Readings with the Positive Lead.



If the Positive Side of the Supply is Grounded, Connect the Positive Test Probe to Ground and Measure Voltages with the Negative Test Lead.

closes otherwise. The voltage drops across all the resistors are the same and they also have the same polarity.

In figure 4, the negative side of the supply is grounded, and it is convenient and conventional to measure the voltages of the circuit with respect to ground. Thus, all of the voltages of figure 4 are "positive." Those in figure 3 are "negative." In figure 3 the voltages were measured with respect to the positive side of the supply (ground) while in figure 4 the voltages are measured with respect to the negative side of the supply.

Let us continue our analysis with the emitter voltage. In figure 3 the voltage between the emitter and ground is the voltage across R4; this is 1 volt. In figure 4 the voltage between the emitter and ground is not the voltage across R4, but instead is the supply voltage less the drop across R4.

With a 6-volt supply and the emitter +5 volts to ground, the drop across R4 is 1 volt. The 5 volts between emitter and ground represents the combined voltage drops across R2 and the emitter-base junction of the transistor; they are in series with R4 across the supply and together must equal the supply voltage. If we measure across R4 we should have 1 volt, with the emitter side of the resistor being negative, the same as in figure 3.

A similar analysis and comparison can be made for the base voltage of figure 4. In figure 4 the base-ground voltage is 4.8 with the base being positive. The 4.8

volts is the voltage across R2. In figure 3 the base-ground voltage is that across R3. The voltage across R3 in figure 4 is 1.2 volts, the same as in figure 3. In both circuits the base side of the resistor is negative to the lower terminal.

The bias voltage at the emitter junction is 0.2 volt with the emitter being positive to the base. Again, this is the same as figure 3. The collector voltage in figure 4 is positive with respect to ground, but it is also 3.5 volts negative with respect to the positive side of the supply, as it is in figure 3.

In summarizing our discussion of figures 3 and 4, we come to the conclusion that the only difference in the circuits is the manner of making voltage checks, not in the circuit values. In figure 3, the positive side of the supply is grounded and hence it is convenient to measure the circuit voltages with respect to ground (the positive side of the supply). In figure 4, however, the negative side of the supply is grounded and it is now more convenient to measure all of the voltages with respect to the negative side of the supply.

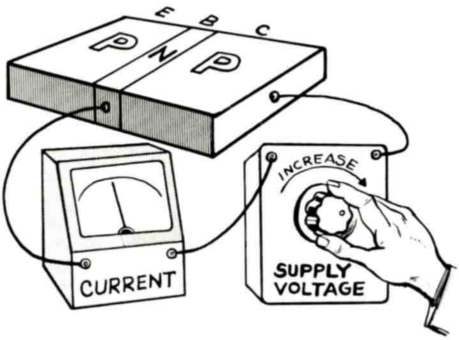
If we reverse our procedure in figure 4 and measure all of the voltages with the positive test prod of the meter connected to the ungrounded (positive) side of the supply, then all of the voltages in the circuit would correspond to those of figure 3. Conversely, if the voltages of figure 3 are taken with respect to the ungrounded (negative) side of the supply, all of the voltage will be the same as those of figure 4.

Figure 5 illustrates the voltages typical of a transformer-coupled amplifier. Compared to the RC-coupled amplifiers we have been discussing, there is no difference in the bias of the emitter junction, but the collector voltage is larger.

With the positive side of the supply grounded, all of the voltages will be negative with respect to ground and thereby the circuit is similar to figure 3. Instead of a coupling capacitor from the preceding stage, the signal is applied to the base by means of the transformer, but this does not alter the DC voltages. The forward emitter bias is 0.2 volt, the same as for figure 3. The bias is "measured" by comparing the negative voltages at the base and emitter.

The collector-ground voltage is very nearly equal to the supply voltage. Decoupling resistor R4 in the collector current path produces a small voltage drop due to the collector current through it. With 5.8 volts at the collector and with a 6-volt supply, the voltage across the resistor is only 0.2 volt.

The DC drop across the collector load, the tuned circuit, is so small that it cannot be measured by ordinary meters. Thus, we assume that there is no DC voltage loss across the coil. With the collector 5.8 volts negative to ground, the collector-base bias voltage is 4.6 volts. This is considerably higher than that of figure 3, but it does not mean that there will be any appreciable increase in collector current. Collector current is determined mainly by the emitter bias and is relatively independent of collector bias.



Increasing the Reverse Collector Bias Produces Little If Any Increase in the Collector Current.

The procedures and analysis given for the RC-coupled and transformer-coupled amplifier stages using a common emitter circuit (figures 2-5) also apply to other amplifier stages regardless of the circuit. As an example, see figure 6, a common-base amplifier.

With a negative-ground supply, the collector is connected directly to ground through the tuned circuit and, as far as DC is concerned, the collector is at ground potential. All of the other circuit terminals will be positive with respect to ground.

The forward emitter bias is the difference between the emitter and base potentials, and for the indicated values this is 0.2 volt. Because the emitter is more positive than the base, this is forward bias. The bias voltages of this circuit may be measured in the manner described for the preceding circuits.

Measuring Oscillator Voltages

In the previous examples concerning bias voltages of transistorized stages, we encountered circuits in which the forward bias of the emitter junction was a fixed value which should remain as constant as possible. There are some transistor circuits in which the operating emitter junction bias varies, and this variation is desirable and important to the operation of the stage.

In the FM communications receiver, we find that the oscillators, multipliers and limiters usually operate in this manner. We will start our discussion with oscillators.

Figure 7 shows a high-frequency, crystal-controlled oscillator circuit used in several Motorola transistorized receivers. The circuit operation is described in the preceding lesson.

If the circuit voltages are measured when the circuit is not oscillating, the voltages will be different from those given in the figure. The greatest difference will be noted in the emitter-base voltage. Without oscillation, the emitter is forward biased as we might expect, and a typical value is 0.2 volt.

An initial forward bias is necessary to make the transistor conduct. As the circuit becomes self oscillating, however, the emitter is reverse biased as indicated in the diagram. This reverse bias is similar to the Class C grid-leak bias established for most vacuum-tube oscillators, in which the grid becomes very negative to the cathode.

In the oscillator of figure 7, the base is driven very negative to the emitter during some portion of each cycle of the feedback voltage. The collector current reaches the point where it cannot increase further and, as a result, the base current increases (the same as already discussed for the limiter in a preceding lesson). This increase of base current through base resistor R2 makes the base more positive than it was originally. In fact, the DC voltage of the base is often more positive than the emitter, producing a reverse bias.

The degree or amount of voltage change taking place at the emitter junction is determined by the circuit and varies with each oscillator. Thus, some oscillators may have just enough feedback to cause oscillation and produce only a small change in the emitter bias. That is, the change may only decrease the forward emitter bias rather than cause reverse bias. Other oscillators may have sufficient feedback that the bias change at the base is sufficient to overcome the forward bias and produce a net reverse bias. We can think of these oscillators as operating in Class C.

There is a problem in measuring the reverse emitter bias for some oscillators, particularly high-frequency circuits. For figure 7, placing the leads of a meter between the emitter and base will probably stop the circuit from oscillating, so that only the initial forward bias of the stage remains. Thus, it is essential to measure the voltages of the emitter and base with respect to ground and compare the difference of the readings.

There is another factor which must be taken into consideration in measuring the voltages at the emitter in figure 7. It is very likely that the loading effect of the leads of any meter other than a vtvm will cause the stage to stop oscillating. Thus, it is important to measure the emitter voltage with a vtvm.

We must also remember that the emitter bias is not a fixed value for this oscillator circuit but, instead, it is variable and changes with both the strength of the oscillation and with the loading effect of the meter when the test leads are connected. For this particular Motorola oscillator, a metering circuit is included to provide for easy tuning (alignment). Thus, except for purposes of trouble shooting within the oscillator itself, oscillation may be checked by the reading of the test set.

Figure 8 gives the circuit of a low-frequency oscillator of a transistorized mobile two-way receiver. The analysis of the emitter bias of the oscillator in figure 7 also applies to figure 8. When the supply voltage is first applied, the stage has an initial forward bias at the emitter junction but, as soon as oscillation starts, the emitter bias swings to a reverse voltage. The amount of this reverse bias is determined to a considerable degree upon the crystal activity, and a wide variation of this voltage can be expected.

The operating frequency of the oscillator of figure 8 is considerably lower than that of figure 7, so that the circuit is not so sensitive to the effects of the meter when the test prods are connected. Either a vtvm or a 20,000 ohms/volt meter may be used to measure the reverse bias. According to the values given on the diagram, with a vtvm we should expect a reading of about 0.5 volt reverse bias.

Frequency Multiplier and Limiter Voltages

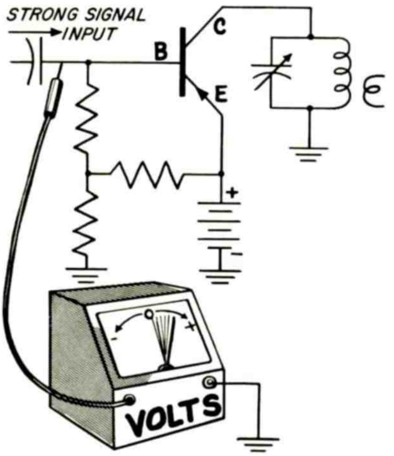
In measuring and analyzing the voltages of the frequency multiplier (following the high-frequency oscillator in the receiver) we can apply the same principles discussed in connection with oscillators.

The purpose of this stage is to multiply the frequency of the oscillator to the frequency required at the mixer (in order that the proper IF will result). This is accomplished by biasing the transistor so that the collector current occurs for only a short period of each cycle of applied voltage, and by tuning the collector circuit for the desired harmonic.

In most receivers the multiplier stage is operated in Class C; that is, the collector current occurs for less than one-half of each cycle of input voltage. Figure 9 gives a typical circuit.

The emitter is initially forward biased, but as soon as the oscillator output is applied, the base swings positive (DC) and reverse biases the emitter junction. For a given circuit, the amount of this bias change and the resulting reverse bias depends upon the signal applied from the oscillator. Thus, in making this measurement, the serviceman must be aware that this reading will vary from unit to unit, according to the "drive" from the oscillator.

The amount of harmonic output of the multiplier and hence the injection signal to the mixer is directly dependent upon the oscillator drive to the multiplier. If this injection voltage becomes too small, the mixer efficiency is



The Signal Strength at the Base of Oscillator, Limiter and Frequency Multiplier Stages May Be Measured by the Change of Base Voltage.

lowered and there is a decrease in the IF signal and a loss in sensitivity. Thus, it is important to have sufficient drive at the transistor base, as indicated by the emitter-base voltage, and the circuit must be properly aligned in order to produce maximum injection voltage at the mixer.

As far as emitter bias is concerned, the analysis of the multiplier stage applies equally well to the limiter stages of the FM receiver. The main difference of these circuits is in the collector load; the multiplier is tuned to a harmonic of the input signal while the limiter, if it is tuned, operates at the same frequency. There is another difference between these stages in that the limiter is operated so that it limits (collector current reaches maximum and cutoff) at a lower drive level than does the multiplier.

Figure 10 shows a typical limiter. The initial emitter voltage is a fraction of a volt in the forward direction, but this will vary with the strength of the incoming signal or noise voltage. This reverse emitter bias continues to increase (the base becomes more positive to the emitter) up to the point where the preceding stage reached full limiting. When this occurs, the input signal does not increase further and there will be no further change of bias voltage.

In performing service work, particularly alignment, the service technician must be aware of "saturation" and realize that once this effect takes place, the base voltage is no longer useful as a means of recording peak indications for alignment. This refers to both the voltage reading at the base, as might be recorded on a voltmeter, and to the reading provided by the test set in the next (discriminator) stage, position 5.

Let us summarize what we have said about the reverse bias at the emitter junction of the oscillator, frequency multiplier and limiter stages of the transistorized two-way communications receiver.

1. The emitter junction is forward biased initially in order

to establish the necessary current in the circuit but, as soon as the circuit starts to operate, the base voltage swings in a positive direction.

2. The amount of change taking place at the emitter junction is determined by the strength of the signal being applied. Where this signal is not very strong, the junction bias may not change very much and the emitter bias remains in the forward direction. If the signal is strong, however, the junction takes on a reverse bias, the base being positive to the emitter (for PNP transistors).

3. The base-ground voltage becomes a convenient means of measuring the amount of signal present or "activity" if we know the amount of voltage change which takes place. This may be accomplished by removing the signal and then reapplying it, noting at the same time the change of DC voltage. For most circuits, this "removal" is readily accomplished by temporarily connecting a capacitor between either the base and ground or the emitter and ground.

4. In using the voltages at the limiter base to determine the signal strength, we must realize that the signal level may be subject to limiting in the preceding stage. For this condition, the limiter will not show any further change, for the input signal to the stage cannot change.

This concludes our discussion of voltage measurements in transistorized circuits, and we are now ready to discuss ohmmeters and resistance measurements.

Ohmmeters and Transistors

Much has already been said about the use of certain types of ohmmeters in checking transistor circuits. We consider the following factors important to the serviceman in using ohmmeters for testing transistorized two-way radio equipment.

First, it has definitely been established that damage can occur to transistors through the use of some ohmmeters. This does not mean that all transistors may be damaged, for some of them are very rugged in this respect. Some transistors have definite limitations as to the voltage and current which they will withstand without damage, however, and for these transistors we need to be very careful. Following this thought further, the serviceman does not always know what "type" of transistors may be involved in every circuit, so it is well to follow certain precautions for all resistance measurements within transistor circuits.

In order to evaluate an ohmmeter for use with transistor circuits, we must know (1) the amount of internal voltage and (2) the amount of current it will deliver to a low-resistance circuit.

It is generally thought that a 4.5-volt source is safe as far as the voltages applied to transistor elements are concerned. Surface-barrier type transistors seem to have the lowest rating in this respect, and it is important to keep the voltage across these units less than 5 volts; do not use ohmmeters with 9-volt and higher supplies.

The second factor in evaluating ohmmeters for testing transistor circuits is the current the meter will deliver on its various ranges. Even though a meter may have a low-voltage internal supply, it may deliver as much as 100 mills (milliamperes) or more to a low-resistance circuit. Most vtvms allow considerable current in the external circuit on their low ohms scales.

Thus, before using any ohmmeter to test a transistor circuit, know the following:

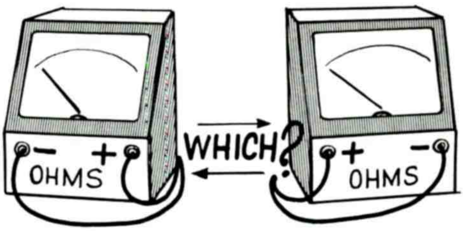
1. The amount of internal battery voltage.

2. The amount of current which the ohmmeter will allow on its various scales.

3. It is also well to know the "polarity" of the internal source; that is, which test lead connects to the positive side of the internal battery.

Using the Ohmmeter

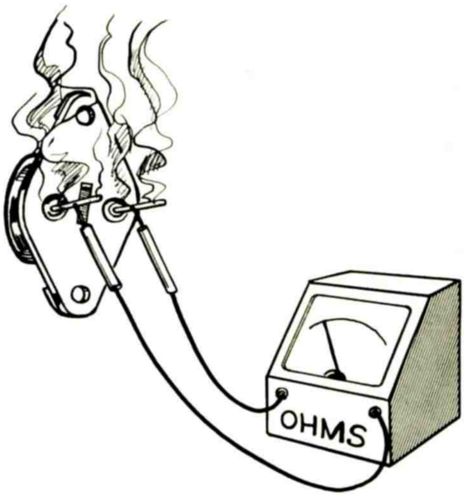
Even though an ohmmeter is "safe" to use in measuring or testing transistor circuits, its intelligent application requires an interpretation of the circuit being measured and the effect of the meter upon the circuit. This can be best illustrated by several examples and, for our purpose, figure 11 is convenient.



Intelligent Use of an Ohmmeter Requires the Serviceman to Know the Polarity of the Internal Battery With Respect to the Test Leads.

Let us assume that the fault has been isolated to this particular stage by some means, perhaps a stage-gain measurement and a voltage check, and the problem is now whether the transistor is defective or if one of the other parts has changed value. The first procedure is to make a resistance or continuity check of each of the parts. Let's start with the resistors.

R3 is a stabilizing resistor connected between the collector and base. The normal procedure for testing a resistor is to place the test leads across the resistor terminals and read the resistance on the meter. This is not a good idea for this circuit, and for several reasons. First, if the test leads are connected to the resistor terminals, we have connected the meter to the base and collector of the transistor.



Some Ohmmeters Deliver Considerable Current to the Circuit Under Test. This High Current May Damage Transistors.

If the test leads are placed so that the negative side of the internal battery is at the base and the positive side to the collector, the transistor junction will be forward biased and the junction will conduct current. The first consideration is that the resulting current through the meter will give a very low resistance indication which will in no manner be representative of the resistance of R3. Furthermore, if the meter furnishes sufficient current and the meter contact is maintained for some time, the transistor may be damaged. In any case, if the meter is connected to forward bias the junction, the meter reading will certainly be misleading.

Next let us suppose that we reverse the meter leads to check R3, so that the junction is reverse biased. The transistor does not conduct, so it does not affect the reading, but we must be very careful that the voltage applied to the transistor does not exceed the voltage rating of the unit. As we have already mentioned, this is particularly true of certain types of transistors.

Even though the transistor is reverse biased and does not conduct and the meter voltage is safe to apply to the transistor, this test will still give an erroneous reading. Why? For the reason that as far as DC is concerned, which is what we measure with an ohmmeter, resistor R2 is in parallel with R3 and the value noted by the ohmmeter will be the resistance of these units in parallel. The bottom of R2 connects to the right side of R3 through the ground connection and through coil L, which for all practical DC purposes has zero DC resistance.

Thus, for any connection of the ohmmeter across R3 we will find an inaccurate indication on the ohmmeter. The only way in which this resistor can be measured with reliability is to disconnect one end of the resistor from the circuit and measure directly across the resistor terminals.

A similar analysis applies to measuring R2, for resistors R2 and R3 are in parallel, as we have just seen. In addition, one end of R2 is connected directly to the base of the transistor and the other connects to the collector through the coil, so that the comments for applying voltage to the emitter junction of the transistor which were just given with respect to R3 apply equally well to the use of the meter for R2 to produce a forward bias as the collector-base junction. The only method of accurately measuring the resistance of this unit is to first disconnect one end.

Measuring the resistance of R1 with an ohmmeter presents the same type of problem encountered with R2 and R3. Meter test leads connected across R1 are also connected to the emitter and base of the transistor, and the internal voltage supply of the meter either forward or reverse biases the junction. If reverse bias is established, the reading will be accurate to the extent that the circuit is relatively free from parallel circuits which might cause wrong readings. For this particular circuit the reading across R1 may be reliable but, in order to avoid any error, it is again good to disconnect one terminal and get the correct value.

A check for continuity at coil L can also result in some doubtful readings, if we are not aware of the effect of the meter upon the transistor. With the positive side of the meter to the top of the coil and the negative test prod to ground, a continuity reading will result even though the coil is open.

The negative side of the battery connects to the base through R2 and the collector junction is forward biased and conducts. The current in the meter is limited by R2, so that the reading indicates higher than normal resistance for the coil; if the very high ohms scale of the meter is used, this difference may not even be noticed. With the test leads reversed so that the transistor does not conduct, there is also a parallel path through R2 and R3.

A unique effect can happen if we place the ohmmeter across capacitor C2 in an effort to check for a short. Suppose the test leads are connected so that the positive side of the battery is towards the emitter. The internal voltage supply can now operate like the regular supply for the stage, and the stage has both forward bias at the emitter and reverse bias at the collector. The condenser will look like a shorted unit as far as the meter indication is concerned.

In making other tests in this or similar circuits, the same principles and analysis of the effect upon the circuit by the ohmmeter will apply equally well. While the specific circuit may vary, the principles do not.

Handling Transistors--Heat Considerations

Until a few years ago, when soldering in electronic circuits the serviceman gave little thought to the amount of heat produced in the components. The advent of selenium rectifiers and printed boards brought some consideration of this factor, however, for they are both subject to damage due to overheating. This problem of heat and damage merits further thought when we introduce transistors instead of vacuum tubes.

Here We See the Basic Tools Required for Fast and Efficient Service of Transistorized Equipment Using Printed Boards.

Heat, usually from high-wattage irons, can cause damage to transistors. Or, if the equipment is left "on" during soldering, even a small rise of temperature may cause high current through the transistor and circuit components. Thus, there are several safety precautions to observe in working with transistorized equipment.

Soldering Transistor Circuits

One of the most practical methods of minimizing the temperature rise of a transistor while soldering is to hold the lead of the transistor with a long nose pliers. The pliers must be between the terminal being soldered and the transistor body, and reasonably close to the soldered terminal. (Any heat which gets past the pliers will be dissipated in the wire length to the transistor.)

Do not allow the iron to remain on the terminal while the iron is heating. It is much better to wait until the iron is hot and then place the iron on the terminal for a minimum length of time--only long enough to complete the job. Where a considerable amount of time is needed to complete a job, it is best to occasionally remove the iron, let the parts cool off, and then proceed.

The transistors in most two-way equipment are soldered directly into the circuit rather than use a socket. This allows for a more permanent electrical connection and avoids one possible source of poor contacts when metallic surfaces oxidize with time. In addition, soldering allows for a better mechanical construction than is afforded by sockets, and this is another very important factor in two-way equipment.

If a socket is used, it is important to make sure that heat due to soldering does not reach the transistor through the socket terminals. It is best to remove the transistor before soldering.

The fact that the outer case of a transistor is held in a clamp does not mean that the transistor is less free from the effects of overheating due to soldering of the leads. Except for power transistors, the case of the transistor is well insulated, heat-wise as well as electrically, from the operating part of the transistor and does not carry the heat away from the unit fast enough to be helpful in this respect. Some leads of transistors are connected to internal shields and do not transfer heat directly to the active elements of the transistor. Therefore, soldering these leads does not readily cause damage.

For power transistors, where the collector is usually in direct metallic contact with the case, heat is quickly transferred to the case and dissipated into the chassis or heat sink on which the transistor is mounted. Such transistors are less likely to be damaged by soldering. In addition, they are larger than other transistors and heat more slowly. Even for these units, however, it is well to avoid overheating due to excessive soldering time.

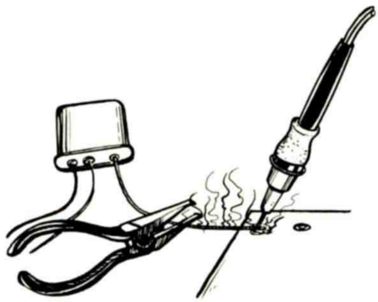
One important factor in the heat problem associated with soldering around transistors is the rating of the iron. Special low-wattage irons are available, and these are rated between 25 and 40 watts. Also, low-melting solder--called "60/40" because of its relative proportion of tin and lead--is helpful in completing a soldering job with a minimum of heat transfer.[1]

Parts Substitution

One good policy which will avoid many troubles is to use the exact replacement part recommended by the manufacturer of the equipment whenever it is necessary to replace a defective component. The only exception to this rule is the case where some equipment must be placed in operation immediately and the exact replacement is not on hand. Even then, it is best to secure the correct part and replace the substitute in the equipment as soon as possible.

There are some components in any equipment which are not so critical that a satisfactory replacement part cannot be used without sacrificing the operation of the unit. On the other hand, there are some parts which are very critical to the point that substitute

1 See "Printed Circuit Service Tips," reference S-8D



A Pliers Holding the Lead Between the Transistor and the Soldered Connection Prevents Overheating of the Transistor Junctions.

components, although they seem to be about the same as the original, do not give optimum service and operation. This is particularly true of equipment found in two-way systems.

Also, in making replacements, parts values are often very critical and components which are "near" the correct value are not permitted. Too many undesirable characteristics may occur if the wrong parts are used. Sometimes a part which seemingly is unimportant can cause unexpected problems. For instance, a wrong-size resistor in the squelch circuit can reduce the squelch sensitivity to the point that the squelch will not open for weak signals; the receiver does not reproduce the incoming messages.

As another example of improper parts substitution, a capacitor may have the same capacitance, voltage rating and tolerance, but it may not be a good bypass at the high frequencies involved. Or the capacitor may change value with temperature changes and detune circuits.

The same reasoning applies to almost all of the parts in this specialized equipment, so that the logic of using "factory" replacement parts is obvious. Even more critical than capacitors and resistors, substitute transistors can cause a lot of trouble. Although not an infallible safeguard, it is well to secure exact replacement transistors and not take a chance on "substitutes."

Even transistors of the same type have considerable variation from one unit to the next. For this reason, transistors of the same type number may be further graded according to their electrical characteristics; they are identified by additional color dots. Where such transistors are specified by the manufacturer, substitutes should never be used.

Almost all stages regardless of their frequency of operation or power level can produce poor operation if the transistors are not replaced by suitable units. Even low-level audio transistors may cause trouble if they are not reasonably identical to the original part. For example, consider the transistor in the preamplifier stage of the microphone. Here the output level of the microphone is very important.

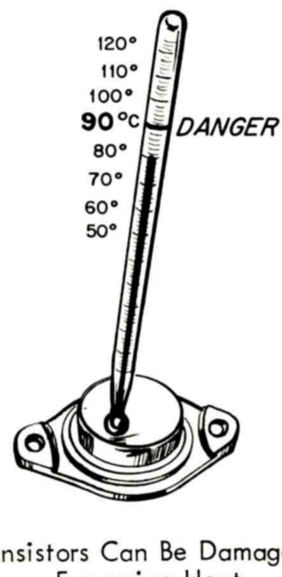
If the microphone amplifier output is too high, all modulating voltages reaching the transmitter will drive the IDC circuit into full clip and cause unnecessary distortion. On the other hand, a transistor with too little gain will produce a weak signal to the transmitter and normal voices will not produce sufficient modulation to provide good system response.

For proper operation of the transmitter, it is important that the microphone output be within certain minimum and maximum limits; substituting the wrong transistor in the microphone may produce an output voltage which is outside of these limits.

Many of the parts associated with the transistorized receiver are different from those to which we have become accustomed. Perhaps the first noted difference is the small size of most of the resistors. Due to the small currents involved in transistors and the relative low impedances of the transistor input and output, small resistance values are paramount. This all adds up to low wattage dissipation in the resistors; small units suffice and invite miniaturization.

Another noticeable characteristic of transistorized receivers is the capacitance and voltage ratings of the capacitors. Due to the low voltage applied, the usual high-voltage capacitors are no longer required. This means that the units may be made considerably smaller. However, due to the low impedances of many of the circuits, the reactance of many of these capacitors must be very low to provide satisfactory bypassing and coupling. As a result, many of the circuit capacitors which before have had comparatively small capacitance are now in the "electrolytic class." That is, the required capacitance is so large that an electrolytic is the only practical answer if the size is to be kept small. Specially developed electrolytic capacitors have been developed for this type of service. These are made from tantalum metal and are generally referred to as "tantalums." They are relatively expensive but provide a means of miniaturization.

Tantalum capacitors are sensitive to reverse polarity. Therefore, when making replacements



Transistors Can Be Damaged by Excessive Heat.

be sure to avoid applying reverse voltage to these units. If the unit should be damaged by reverse polarity, it does not "reform" as do regular electrolytics and the unit will not perform as intended. There are specially built tantalums which will withstand reverse polarity, but they are more expensive and are used only where it is essential to do so. These are the "foil" type tantalums.

Most low-voltage, high-capacitance electrolytics exhibit a greater amount of leakage current than found in higher voltage units. Using a 6-volt supply, such as found in most bench-type testers, a leakage of at least 10 microamperes is permissible after the unit has had a chance to reform.

Printed Boards and Modular Construction

Printed boards are not exclusive to transistor circuitry, for vacuum-tube equipment such as TV receivers, test equipment, etc., have used printed boards rather extensively in the last several years. Besides its obvious advantage of reducing the cost of production, printed board construction offers other advantages. Very important is the reduction of wiring within the equipment, and there is no service problem of lead dressing.

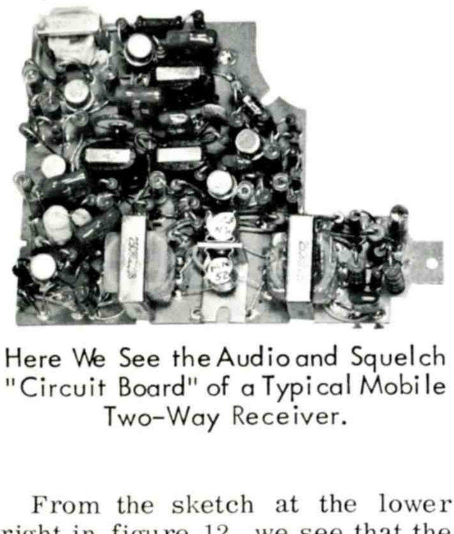
Transistors, due to their small size and weight, offer greater opportunities for compact equipment in conjunction with printed board techniques, to the point that small modular construction has allowed extreme compactness and miniaturization of what was once large, heavy equipment. A good example of this is the pocket-size communications receivers having extremely good sensitivity.

Because printed boards are almost inherently a part of transistorization, this lesson dealing with the service of such equipment must include printed board service techniques.

One of the first problems encountered by the serviceman when troubleshooting transistorized equipment is the location of the various parts. In many cases the serviceman looks at the bottom of the board which has a lot of printed circuits. In order to locate the various circuit terminals, full use must be made of the service material which is found in the instruction manual.

Perhaps the most useful service information is the wiring diagram with respect to the printed board and the parts which are connected to the various terminals. An example of such a diagram is shown in figure 12. This is the wiring of a Motorola pocket receiver using printed boards and modular construction. This, used in connection with the section layout at the lower right of the figure and the schematic allows the serviceman to readily locate all the circuit terminals and troubleshoot the receiver.

As an example of what can be accomplished by this material, suppose that we wish to make a quick check of the first audio stage, for we suspect from the operation that the receiver is squelched at all times and is not opening when a signal comes in. This is also evident from the fact that the complete rotation of the squelch control does not open the receiver and allow the noise to be heard even when there is no signal.



Here We See the Audio and Squelch "Circuit Board" of a Typical Mobile Two-Way Receiver.

From the sketch at the lower right in figure 12, we see that the audio amplifier is in the "L" shaped module, and from the schematic diagram, not shown here, we find that the base of Q12, the first audio amplifier, should have +2 volts when squelched and -0.3 volts when unsquelched. In figure 12 we locate the portion of the board that connects to the base of Q12 and find that the voltage is always about 2 volts positive regardless of the position of the squelch control. This confirms our conviction about the nature of the trouble in the receiver and may now continue to check further on the squelch circuitry. We follow the same general procedure in locating the various circuit terminals and in making voltage tests.

Repair of Printed Boards

Proper soldering techniques are essential to the maintenance of printed boards, and much has already been published on this subject. We will only attempt to summarize at this time what has already been said. A soldering iron of about 40 watts is recommended for this procedure and 60/40 type solder with a little silver added is best.

One trouble which might be encountered with printed boards is fine, hair-like cracks which occur but are not discernible with normal viewing. A good lighting system is essential, and a magnifying glass is also useful. Commercial units incorporating both these features in a single assembly are available. Hairline cracks are often detected by making voltage or resistance tests, in addition to a visual inspection.

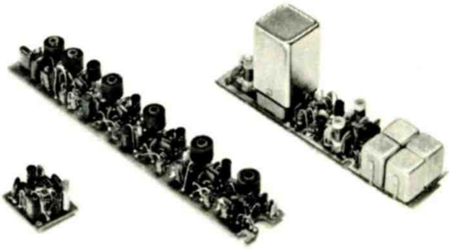
Breaks in the plating are repaired by means of a jumper wire across the break. Where the board as well as the plating is cracked, follow the suggested procedure included in Reference S-8D.

As shown in figure 12, many of the stages are built as a small module. Each assembly is extremely small and, in cases where time is an all important factor, it may not be wise to perform troubleshooting and repair work within any one module. Because they are so small and incorporate but a few parts, it may be more efficient to replace the complete module known to be bad rather than spend the additional time required to further isolate the fault. The defective module can be repaired at some future time and at the convenience of the technician. [2]

Servicing Transistorized Power Supplies

For the purpose of this lesson, we shall not be concerned with the manner in which the switch type transistor power supply operates; instead, we shall determine the proper procedures to follow in servicing these supplies. There are several operating characteristics of these supplies which make it convenient for the service technician to analyze the nature and location of the trouble. We shall look at these characteristics carefully.

First, the output voltages of the supply varies with the load or amount of power delivered by the supply. The greater the load current, the lower the output voltage. The higher current through the various components produces larger voltage drops, causing a lower voltage at the output terminals. (This characteristic is common to all unregulated power supplies.) Thus, by carefully observing the output voltage, it is possible to estimate the relative load on the supply.



Starting at the Left, We See the Low-Frequency Oscillator, 455-KC IF and High-Frequency Oscillator-Multiplier Sections of a Transistorized Receiver.

Another important factor, and this one is unique to this switch type of power supply we are talking about, is the change in the operating frequency as the load increases. As the load increases, the frequency decreases. If the load increases beyond a certain point, the switching action stops altogether and there is no output voltage.

Also, where the radio is operated in a relatively quiet location, there is a slight "singing" sound heard from the power transformer; according to the "pitch" of this sound, which is the operating frequency, we can deduce the load on the supply.

The fuses also help to determine the nature of the trouble. For example, if a fuse burns out as soon as the set is turned on, we have a different problem than if the fuse burns out only intermittently, or only when the transmitter is being used.

2 See references S-8A, S-8B, S-8C and S-8D.

These are the things we will make use of in troubleshooting the transistorized power supply. We will start our discussion by assuming that some trouble has been traced to the supply--at least it seems to be in the supply--and the fuses blow as soon as they are replaced. The radio is being operated on the test bench in an effort to determine the specific trouble. Figure 13 gives the schematic of a typical transistorized supply which operates either the receiver or the transmitter of the two-way radio set. This supply was chosen because of the possibility of different sources of trouble, compared with the power supply used with the two-way radio having a transistorized receiver, in which case the power supply operates only during transmit.

Fuses Blow

For the symptom of continuous blowing of power supply fuse F1 (not F2, the fuse to the receiver and transmitter filaments, etc.), it is probable that a transistor in the power supply is defective. Only a direct short in the primary circuit will continue to blow fuses and, in almost every instance, this will be a transistor. Conversely, if the fuse does not blow, it is not likely that the transistors are bad. Thus, the fuse to the transistor switch circuit, F1 in the diagram, is a very good indication of the condition of the transistors.

If the fuse is blown it is well to try a new one, before doing any other troubleshooting, for occasionally a fuse will blow without anything being wrong in the supply. With a new fuse installed, the unit can be put back into operation. Where fuses continue to blow, however, we can be reasonably sure that one of the transistors is bad and requires replacement. Although the transformer could cause the same symptom, it is not often likely to be the source of trouble.

Testing Transistors

The transistors found in power supply switching circuits are the power transistor type and require a power transistor tester. If one is not available, a quick check on the transistors can be made by following the procedure shown in figure 14. Here an ohmmeter--any kind is okay for power transistors--is connected with the positive side of its internal battery to the emitter and the other meter test lead to the collector.

The meter adjustment should be set so that the pointer is somewhere near the middle of the meter dial. The base is then alternately shorted to the emitter and collector and the changes of meter current observed. With the base to the emitter, the current should decrease; when the base is connected to the collector, the current increases.

We need not be concerned with the amount of change in determining the condition of the transistor, for it has been found by experience that these transistors will be completely bad, or they will be okay to use in the supply. Thus, if the meter readings increase and decrease, the transistor is probably normal and does not require replacement. If the changes are not as indicated, however, the transistor is defective, and a new unit should be installed.

It is not essential that the transistors in a power supply be matched. As long as they check near normal, they will operate satisfactorily.

Replacing Transistors

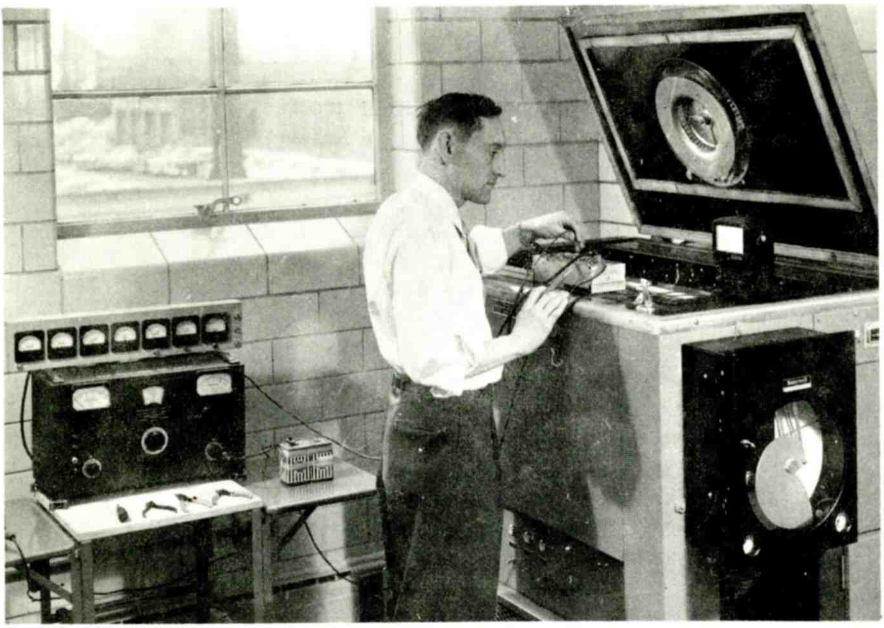
In replacing the transistors of many power supplies, the transistors are electrically insulated from the heat sink by thin mica washers. This allows for operation from either a positive or a negative grounded electrical system in the vehicle. At the same time that the transistors are isolated from the heat sink, a special lubricant is used to maintain good heat transfer from the transistor to the sink. Thus, always be sure that the transistors are not shorted to the heat sink, particularly after making a replacement.

Also, when a transistor is replaced, it is well to make a check on the primary circuit before turning on the supply. This is particularly true of the base circuit of each transistor. If the base circuit happens to be shorted to ground, the transistor will probably burn out as soon as the supply is turned on. The parts within the dashed lines in figure 13 are located on the front panel of the radio assembly and should be checked carefully for a short. This also applies to the cabling between the power supply chassis and the transistors.

Operational Test

If a transistor has been replaced and the primary circuit has been checked for a short, the base circuit of the transistor in particular, it is permissible to turn on the power supply for a "quick check." That is, it is okay to turn on the supply and determine if the switch circuit starts, and listen to the frequency of the switch operation. This quick check will not allow enough heat to burn out the transistor even though the secondary is overloaded. Of course, if the supply is left on for too long a time, there may still be something in the power supply or the load which will cause the transistors to go bad due to excessive heating.

Following this thought, every time a supply is turned on it should be an automatic procedure for the serviceman to listen to the "sound" of the switch circuit. If the frequency is too low, it is not wise to let the supply on for any length of time; leave it on only long enough to make quick tests. If the frequency, on the other hand, is near normal, the load cannot be excessive to the point that short-term operation will cause damage. There is now sufficient time to make voltage checks on the equip-



In Designing Transistorized Equipment, It is Important to Check for Operation at All Temperatures.

ment and perform what other service work that must be done while the supply is operating.

If the serviceman is to utilize the operational frequency of the power supply as a means of judging the operation of a supply, it is necessary that he know the sound of these supplies under normal operation. Without this pre-experience, he will not be capable of reaching quick, valid conclusions.

It is always good to check the supply on both standby and transmit operation, for there is always the possibility that the trouble is in the transmit section of the supply or in the transmitter itself rather than in the receiver or the low-voltage section of the supply.

Overloads and Transistor Burnouts

There is one main danger of operating transistor power supplies when they are overloaded. We already know that the operating frequency decreases with an increase of load. We found further that the switch circuit will even stop operating if the overload is too great. There is a dangerous point where the overload is not sufficient to cause the switch to stop operating, but at the same time is sufficient to cause the transistors to be damaged by excessive heating if the supply continues to operate. Thus, do not continue to operate the overloaded transistor supply even though the switch circuit operates.

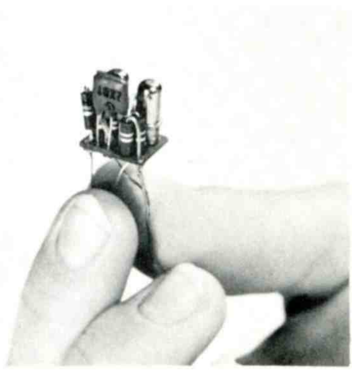
Too heavy an overload prevents the circuit from operating; under this condition, the transistors do not draw any appreciable amount of current and will not be damaged if the supply is left on. Troubles for this type of inoperation are almost always complete or near-complete shorts in the secondary circuits (or in the receiver and transmitter), and may often be found with the use of an ohmmeter. Again it is advisable to compare the operation on both the receiver and transmit position. If the short is evidenced for both positions, the fault is probably internal to the supply.

A short on only the transmit or receiver position may indicate a short in the transmitter or receiver rather than inside the supply. Because the low-voltage section of this particular supply is used for both the receive and transmit, a short here will show up on both positions. On the other hand, a short in the high-voltage section of the supply will be evidenced only when the equipment is operated in transmit. Here the short could be internal to the supply or it might be in the transmitter; a further check to isolate the location of the trouble will be necessary. For the purpose of this lesson, however, we will assume that the troubles are all internal to the supply.

Shorts in the Filter Sections

Neglecting shorts in the wiring...which must be considered as a possible source of trouble in actual equipment...there are only two likely points where shorts might occur inside the power supply, namely the filter capacitors and the rectifiers.

Electrolytics are more likely to have a partial short than a complete short. That is, they develop a leakage which allows a higher than normal current through them, but at the same time, they do not look like a complete short (zero resistance). Because they are not often completely shorted, filter condensers do not normally stop the supply from operating, but merely cause a reduction in operating frequency and lower output voltages. These partially shorted capacitors are often found by any or all of the following:



Here We See a Complete Stage (Module) of a Modern Pocket-Size Receiver.

1. The capacitor feels "hot" when touched.

2. They start to "leak" or show other physical signs of being bad.

3. Measure with a capacitor bridge for shorts (power factor).

4. Replace and compare the operation. (The wiring to the capacitor may be disconnected for a quick check.)

Although electrolytics may "open," there will not be any evidence of this as far as the supply parts overheating or the fuses are concerned; there will be no "short" to cause any damage. Instead, the inadequate filtering will show up in the operation of either or both the receiver and the transmitter.

Rectifiers

Power supplies in two-way mobile radio equipment may use either selenium or silicon rectifiers. The characteristics of these two units vary considerably as far as typical troubles are concerned. Selenium diodes are more likely to develop leakages rather than complete shorts, so that they look like a medium-low resistance. The resulting additional current causes a lower output voltage. When the output voltage at the rectifier is low, it may be well to install new rectifiers and compare the results.

Silicon rectifiers, by contrast, are most likely to short completely so that they stop the circuit from operating--the switch will not function. Shorted rectifiers are readily found by a resistance check of the rectifiers, measuring in both directions. These units are often mounted on spring clips and can be removed as easily as a fuse. A good rectifier will usually show less than 100 ohms in one direction and somewhere around 1000 times this resistance in the other direction.

Output Voltages

The output voltages of the power supply are convenient in evaluating the operation of the supply. This is particularly true when this information is used with the "sound" or operating frequency. If the output voltage is within 10 or possibly 15% of its rated value, it is possible that the supply is operating normally. We must always remember that these voltages vary with the degree of loading; the transmitter loading, in particular, varies considerably with the transmitter adjustments.

If the output voltages are too low, do not turn the supply on for any great length of time. It is possible to burn out a transistor by continued excessive current. It is probably okay to turn the supply on for short intervals in order to make tests, but do not let the transistors get too hot. This is a major source of transistor burnouts.

The output voltages also vary considerably with the primary voltage. In the vehicle, the primary voltage should be somewhere near 13.5 volts, if the output voltages are to be correct. This takes into consideration that for transmit there will be about 1-volt drop across the cables, so that the voltage at the power supply input is about 12.5 volts. There is less cable drop during standby, so the voltage to the supply should be around 13.5 volts during standby. These quoted voltage values will vary considerably with different models and types of two-way equipment.

Inoperative Switch

If the switch circuit refuses to operate, suspect a defective primary circuit, a bad transistor, or a direct short across the secondary. Make a check of the transistors as already suggested, and check the primary circuit. Do not overlook the possibility of a defective fuse or a poor connection.

In order to check the secondary circuits for a short, it is permissible to remove one end of the silicon rectifiers from their sockets, or remove the connections of the transformer secondary if the rectifiers are not in clips. This removes all the load from the secondary winding and the switch circuit should work provided the primary is okay, the transistors are good, and the transformer is normal. The switch frequency will be rather high for this test, for there is no load.

Since the transformer is the least likely source of trouble, it should be the last unit which we suspect. It is designed for operation at a high frequency and should not be tested by applying a known 60-cycle AC voltage to one winding and measuring the other voltages. In fact, except for a general continuity test of the windings and a resistance check for a short between windings, there is little that can be done "in the field" about testing the transformer. The only reliable method is to try another transformer and compare the results.

Test Bench Operation of Transistorized Receivers

One problem arises in connection with the operation of transistorized receivers on the test bench, where the power source is usually an AC operated supply. The supply found in the average service shop is satisfactory for the vacuum-tube type receiver, but there is a problem of inadequate filtering for the operation of transistorized receivers.

The average AC operated supply has too much ripple (due to insufficient filtering) in the output to provide normal operation of the transistorized receiver. As a result, there is a predominant hum in the speaker and the quieting measurements of the receiver are affected. There are two practical solutions to this problem. First, a regular 12-volt storage battery may be placed across the power supply output terminals. Second, additional filtering may be added.

A storage battery across the output terminals acts like a very large capacitance and in most cases provides the additional filtering needed to restore normal operation. The problem of maintaining the battery at full charge is readily solved by allowing the power supply to act like a charger for the battery.

The second procedure of adding a filter to the primary power supply is a very satisfactory solution to the problem, provided the filter section is adequate. This, in turn, is determined to some extent by the amount of initial filtering in the supply. Usually the combination of a heavy choke (capable of handling the current drain of the equipment) and a large capacitor (at the output) will provide the necessary filtering. The capacitor is usually a 10,000-25,000 mfd unit rated around 20 volts DC and a DC surge voltage rating of about 30-40 volts. The filter capacitance in the power supply acts like an input capacitance to the added filter section. Added capacitance at this point will improve the filtering and the regulation, but it is not necessary if the supply has a reasonable amount of internal capacitance. The circuit of a typical filter section of this type is shown in figure 15.

While an additional filter is added to the power supply for bench operation of the transistorized receiver, the operation of the transmitter does not require the extra filter. Furthermore, the DC drop across the choke during transmit may produce a low voltage to the transmitter. A higher output voltage is possible by shorting a heavy wire across the choke terminals during transmit operation. This will also improve the regulation, for, unless the choke has an exceedingly low internal resistance, the added drop produces a poorly regulated output voltage.

Summary

Let us summarize briefly what has been said about troubleshooting the power supply:

1. In working with the transistorized switch type of power supply, we make use of the output voltages, the frequency of operation as determined by the "sound," and the fuses.

2. If replacement fuses also burn out, one (or more) of the transistors is probably defective and must be replaced.

3. Transistors may be tested with a regular tester or by the simple method shown in figure 14.

4. Replacement transistors must be electrically insulated from

the heat sink in some applications, but a good thermal contact is maintained by a special silicone grease on the washers.

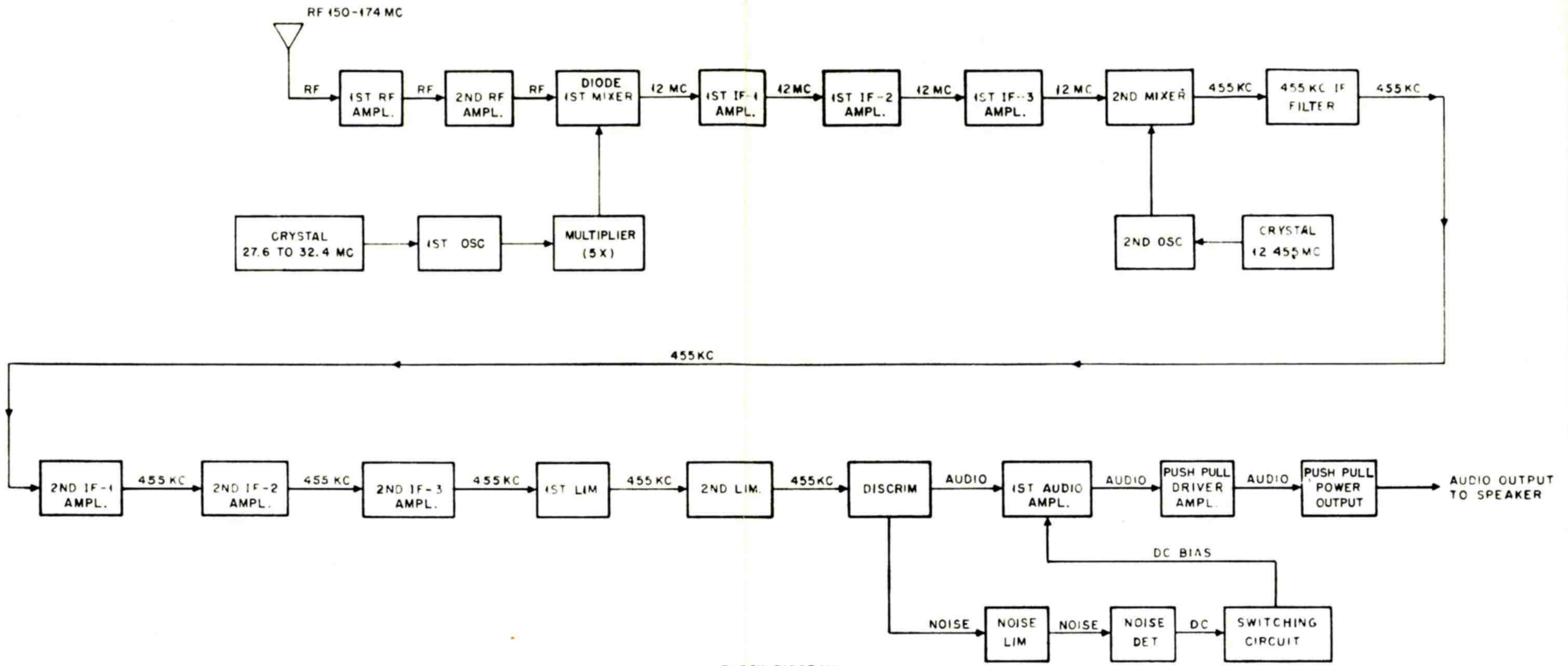
5. Transistors should be tested for a short to the heat sink, and the base circuit should be similarly checked before operating a supply with a new transistor.

6. A heavy load will stop the switch from operating. A heavy load, but not a complete short, causes the switch circuit to "slow down" in frequency and this change can be heard. The output voltage of the supply also varies in the same manner as the operating frequency.

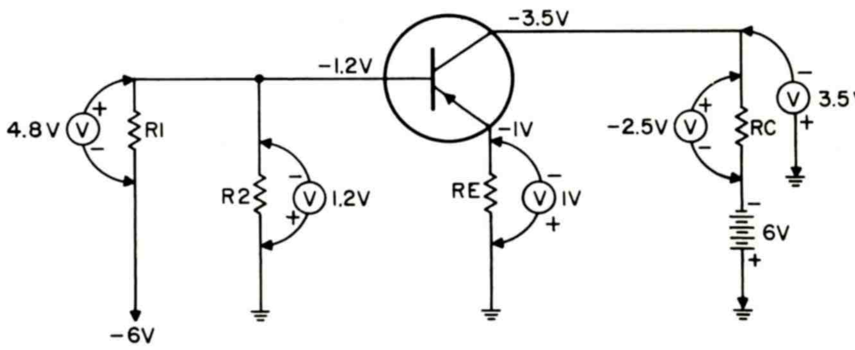
7. Electrolytic capacitors and selenium rectifiers may become leaky and overload the supply. For an overloaded supply, do not leave the supply on for long periods as this can cause the transistors to overheat and burn out.

8. Silicon rectifiers are more likely to short completely rather than develop some leakage. Silicons may be checked by their front-to-back resistance.

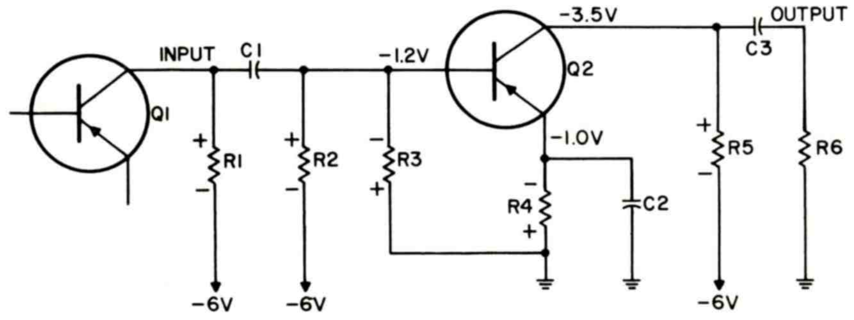
STUDENT NOTES



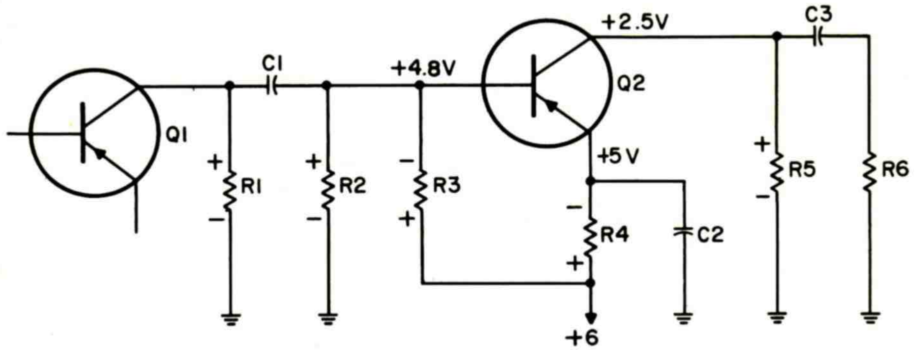
BLOCK DIAGRAM
FIGURE 1



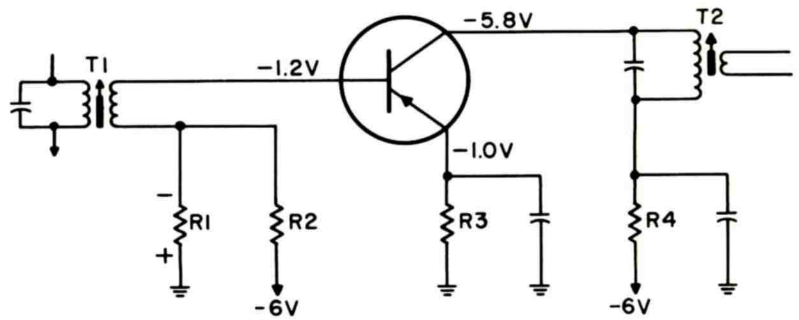
VOLTMETER READINGS IN
TRANSISTOR CIRCUITS
FIGURE 2



RC-COUPLED AMPLIFIER
FIGURE 3



RC-COUPLED AMPLIFIER
FIGURE 4



TRANSFORMER COUPLING
FIGURE 5

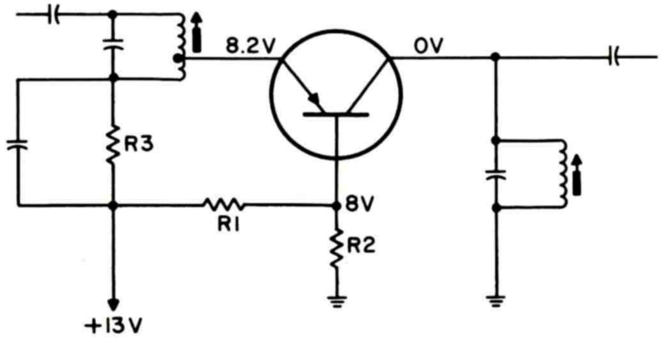
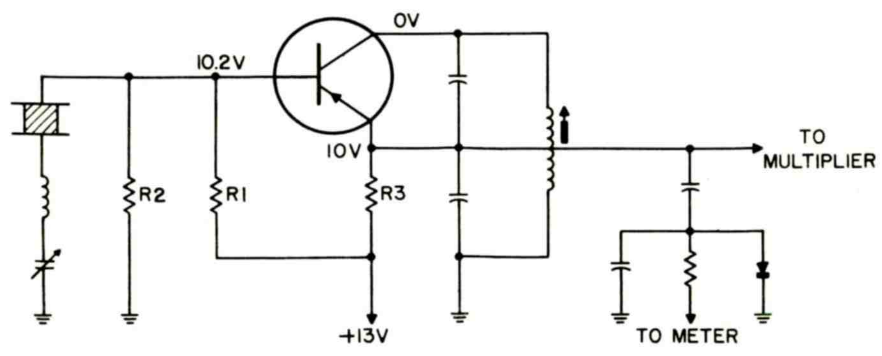
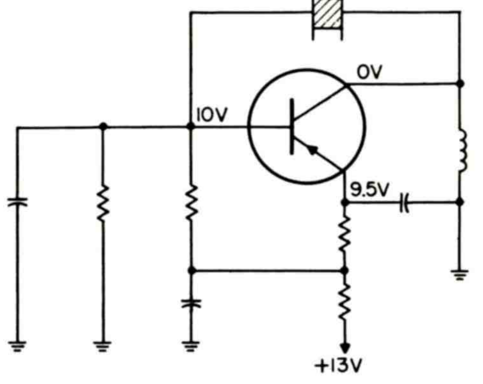


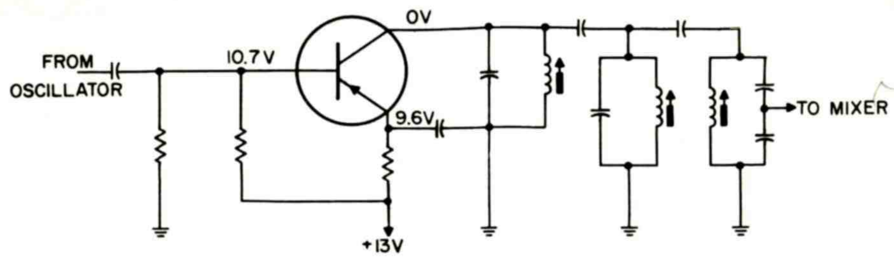
FIGURE 6



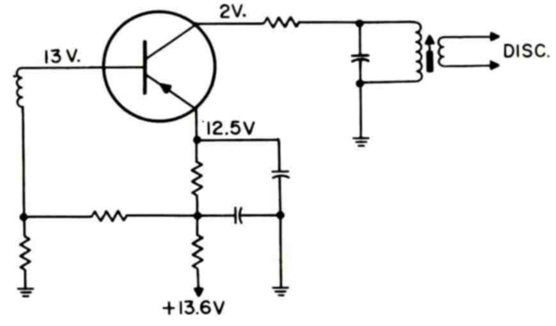
HIGH-FREQUENCY OSCILLATOR
TWO-WAY COMMUNICATIONS RECEIVER
FIGURE 7



LOW-FREQUENCY OSCILLATOR
TWO-WAY COMMUNICATIONS RECEIVER
FIGURE 8



FREQUENCY MULTIPLIER
TWO-WAY COMMUNICATIONS RECEIVER
FIGURE 9



455-KC LIMITER
FIGURE 10

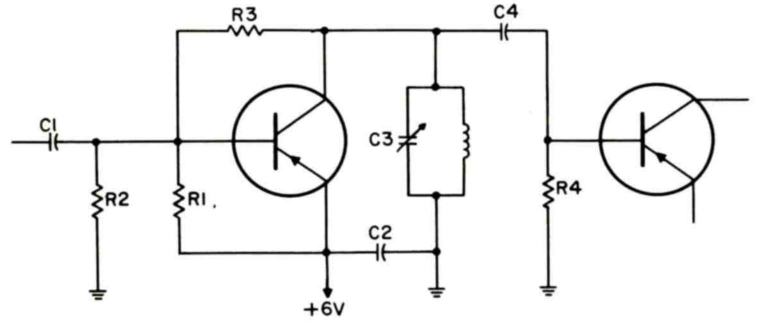
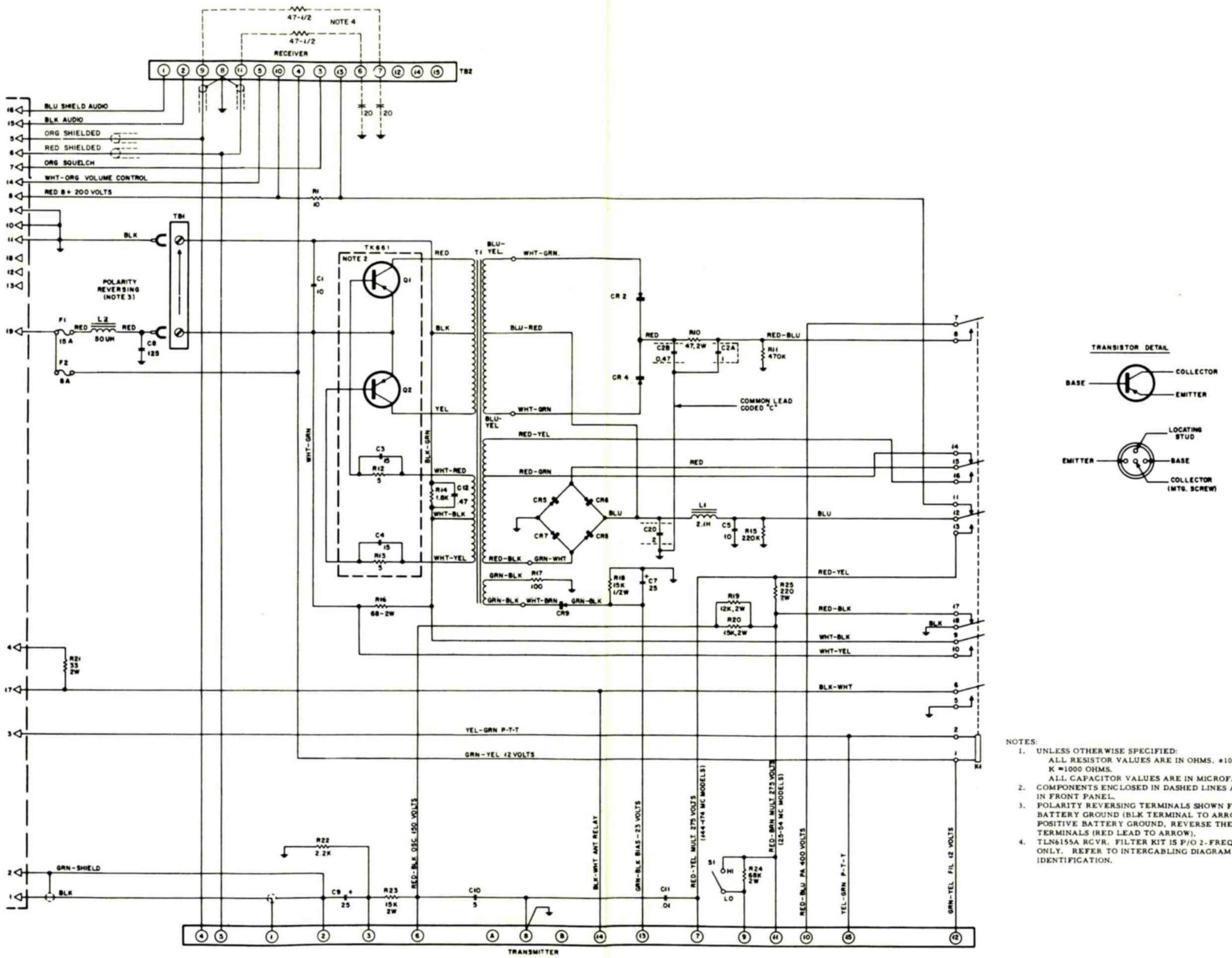


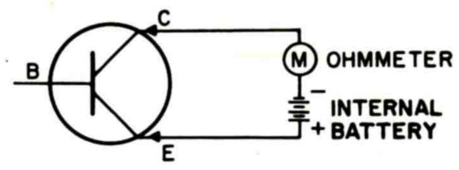
FIGURE 11



TRANSISTOR "SWITCH" POWER SUPPLY
FIGURE 12

NOTES:

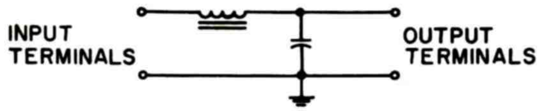
1. UNLESS OTHERWISE SPECIFIED:
   ALL RESISTOR VALUES ARE IN OHMS, ±10%, 1 WATT
   K =1000 OHMS.
   ALL CAPACITOR VALUES ARE IN MICROFARADS.
2. COMPONENTS ENCLOSED IN DASHED LINES ARE LOCATED IN FRONT PANEL.
3. POLARITY REVERSING TERMINALS SHOWN FOR NEGATIVE BATTERY GROUND (BLK TERMINAL TO ARROW). FOR POSITIVE BATTERY GROUND, REVERSE THE TWO TERMINALS (RED LEAD TO ARROW).
4. TLN6155A RCVR. FILTER KIT IS P/O 2-FREQ. RADIO SET ONLY. REFER TO INTERCABLING DIAGRAM FOR PARTS IDENTIFICATION.



TEST CIRCUIT FOR POWER TRANSISTORS

1. CONNECT OHMMETER WITH POSITIVE SIDE OF INTERNAL BATTERY TO THE EMITTER AND NEGATIVE TO THE COLLECTOR.
2. USE SUITABLE SCALE AND ADJUST FOR CENTER-SCALE READING.
3. CONNECT BASE TO EMITTER = READING SHOULD DECREASE.
4. CONNECT BASE TO COLLECTOR = READING SHOULD INCREASE.

FIGURE 13



POWER SUPPLY FILTER SECTION
FIGURE 14

national

MOTOROLA

RADIO COMMUNICATIONS

service