RCA VICTOR

RADIO – "VICTROLA"

SERVICE CLINIC

Transistors

INTRODUCTION TO
THEORY – CIRCUITS

PREPARED BY COMMERCIAL SERVICE
RCA SERVICE COMPANY, INC., CAMDEN 8, N. J.

A Service of Radio Corporation of America

FOREWORD

The purpose of this booklet is to present the theory of transistor operation; to give a brief insight into transistor manufacturing techniques; and to introduce basic circuits as compared with similar circuits used in equipment having vacuum tubes.

It is made available by the RCA Victor Radio and "Victrola" Division, and RCA Victor distributors, to assist the service technician in understanding transistors and their uses in RCA Victor radio and "Victrola" instruments.

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TABLE OF CONTENTS

INTRODUCTION TO TRANSISTOR THEORY AND CIRCUITS

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INTRODUCTION

The heart of early radio receivers was the crystal detector, figure 1, which generally used a small piece of galena or silicon. This crystal allowed current to pass in only one direction and acted as a rectifier to produce audio variations. Going further than this with crystals seemed unimportant at that time as the vacuum tube had just come into being, and was proving superior, in many ways, to the crystal detector.

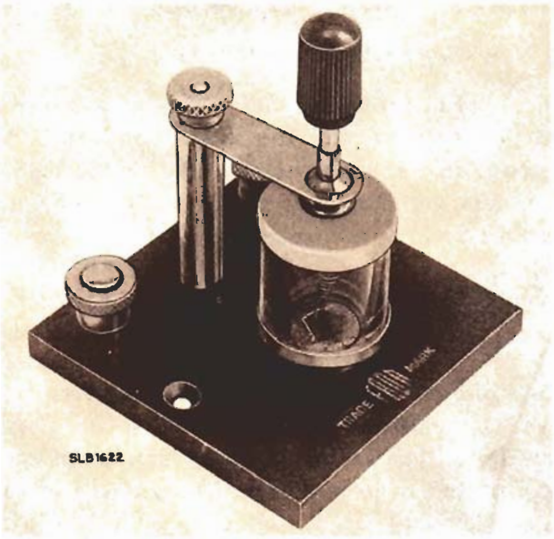


Fig. 1—Early Crystal Detector.

However, engineers continued to investigate crystals, and gradually found out many things about them which have recently made it possible for crystals to do many of the things that a vacuum tube will do, and in some cases, better. First, of course, came the fixed crystal which for some years has been used as a rectifier where small size, good sensitivity, and low noise was required. Engineers did not, however, stop with the fixed crystal, but eventually came up with the transistor. One of the advantages of the transistor is its comparatively small size.

Transistors have been available for some time and engineers are beginning to appreciate the many superior qualities as compared to the vacuum tube. Transistors are smaller in size, figures 2 and 3, and weigh less; they have no filaments and therefore consume less power; they have long operating lives; they are solid in construction and extremely rugged; they are not subject to microphonics; they require no warm-up; they can be made impervious to the weather; and finally, transistor circuitry is greatly simplified over tube circuitry.

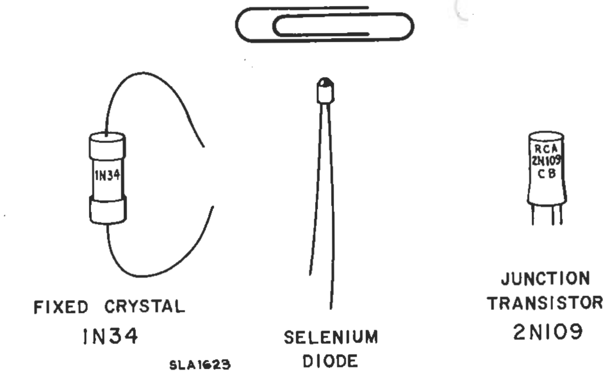


Fig. 2—Transistor Size Comparison.

Transistors will certainly lend competition to many functions now performed by vacuum tubes. There will be many cases in which it will be possible to replace tubes with transistors and reduce the cost and increase the convenience or efficiency of the circuit. It is also possible that some entirely new field of electronics will be made possible by the use of transistors.

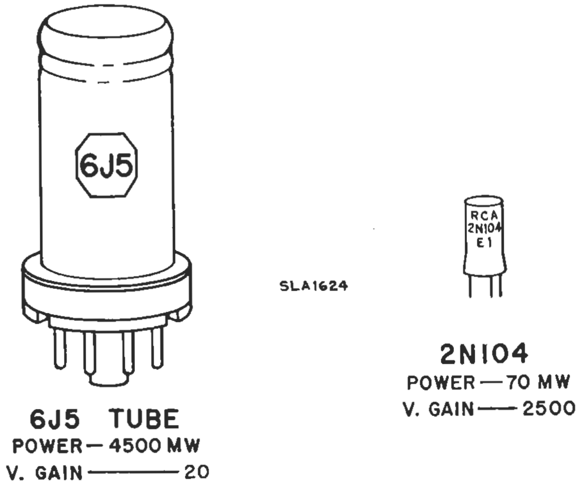


Fig. 3—Transistor Power and Gain Comparison.

THE GERMANIUM ATOM

Before looking into the operation of a transistor it will be useful to look at the structure of the atoms of several materials. We are mainly interested in germanium, silicon, antimony, arsenic, aluminum, and gallium. A germanium atom is represented in the graphical diagram (a) in figure 4. The atom has 32 protons in its nucleus and 28 tightly bound electrons around it, plus 4 valence electrons in the outer ring. Please remember that this is a two dimensional drawing of a subject that has three dimensions.

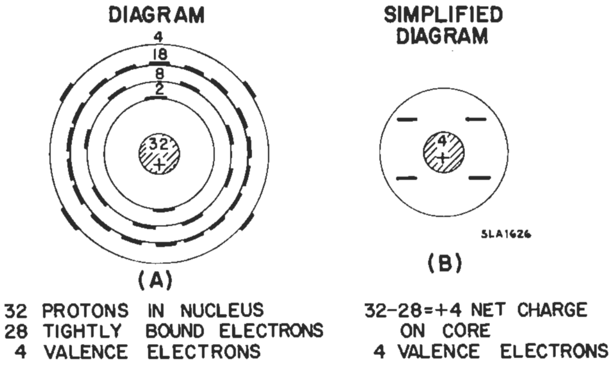


Fig. 4—The Germanium Atom.

The valence electron is very important in the study of solids. *Valence* means the degree of combining power of an atom. The outer shell of a solid is incomplete, and the valence electron is that part of the atom responsible for its ability to bind chemically with other atoms. When atoms bind together through their valence electrons, it is called an "electron—pair bond" or "covalent bond" and is one of the principal building blocks of chemistry. Consequently, the valence electron will attempt to pair off with those of another atom in order to complete the outer shell.

We are mainly concerned with the net charge on the core of the atom and the valence electrones surrounding it. Therefore, we can simplify the previous diagram of the germanium atom as shown in figure 4(b). Here we have shown the net charge (which is the total number of protons in the nucleus minus the tightly bound electrons which do not enter into any chemical reactions) as the core, and the four electrons (negative charges) which are the valence electrons.

THE SILICON ATOM

In figure 5(a), we see a silicon atom completely diagrammed showing the 14 protons in its nucleus and the 10 tightly bound electrons around it in two rings, plus the 4 valence electrons of the outer ring.

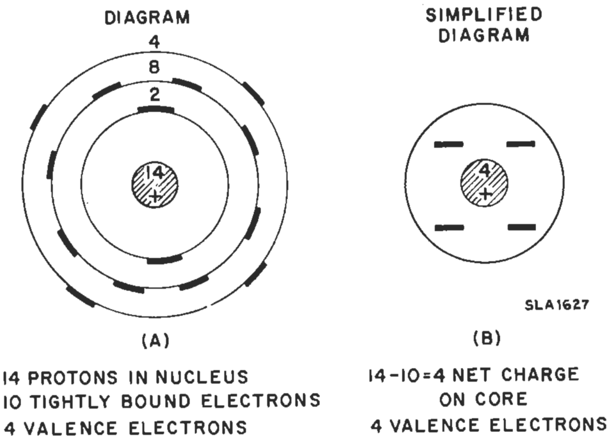


Fig. 5—The Silicon Atom.

In the simplified diagram (b) we show only the net charge on the core, and the valence electrons. You will notice that it looks exactly like the germanium atom, in fact, germanium or silicon can be used equally well in the making of transistors.

ATOM STRUCTURES OF SEVERAL SUBSTANCES

In figure 6 we show the simplified diagrams of the atoms of a number of substances used in the making of transistors. The germanium or silicon atom is represented by (a) which we have already discussed. The antimony or arsenic atom by (b). Here we notice that there is a net charge of 5 protons, and 5 valence electrons. The atom structure of aluminum or gallium is shown in figure 6(c). Here again we note that it is different from germanium or silicon in that there are only 3 protons in the net charge of the core, and 3 valence electrons.

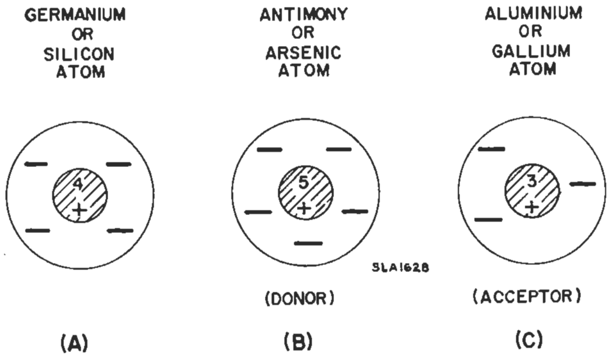


Fig. 6—Simplified Atom Diagrams.

GERMANIUM CRYSTAL

Figure 7 shows the plan on which a pure germanium crystal is formed. Each atom has four neighboring atoms, all located the same distance away, and each the same distance from each other. If you can visualize this, you will see that four is the largest number of bodies that can be located around each other with equal separation from each other, or in other words, be equidistant from each other.

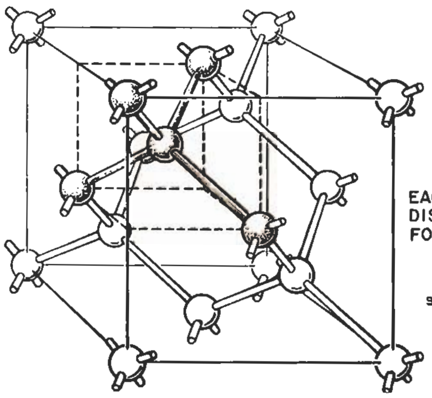


Fig. 7—The Germanium Crystal in 3 Dimensions.

COVALENT BOND STRUCTURE IN CRYSTALS

Normally we are interested in the production of anything as near perfect as possible. However, this is not true in the case of transistors, where the insertion of impurities, with control, is the basis for performance operation. Before discussing the imperfections in a germanium or silicon crystal, it will be necessary to discuss perfection.

Figure 8 illustrates the atomic structure of a perfect germanium or silicon crystal as pictured in figure 7, only now it is shown in a diagram where all atoms are pictured in a single plane rather than in space. You will note that each atom is surrounded by four other atoms, symmetrically placed. An "electron-pair bond" or "covalent bond" is formed between each atom and the one next to it, with the bond being shared equally by the two atoms at its ends, as indicated by the shaded areas and negative signs. This crystal, in the perfect state, has its bond structure complete and every atom is at rest in its proper place, with no atoms or electrons missing or squeezed into wrong places.

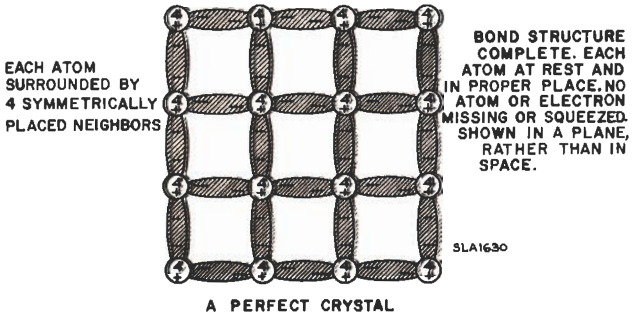


Fig. 8—The Covalent Bond Structure of Germanium or Silicon Crystals.

In this case, a perfect crystal, the valence electrons are all held in covalent bonds. Equilibrium exists, and the valence electrons are all bound to their respective nuclei. When this condition exists, the crystal is a fair insulator.

Germanium or Silicon "N" Type Crystal

Now that we have discussed a pure crystal, we will turn our attention to the effect of inserting impurities into the pure crystal. Actually, pure germanium has impurities to the extent of 1 part in 1 billion, but this amount of impurity has no application in the field of transistors. To provide adequate carriers of current in the germanium crystal, impurities are added, about 1 part in 100 million. This impurity may be antimony, arsenic, aluminum, or gallium.

Figure 9 illustrates the effect of adding arsenic or antimony to the germanium or silicon crystal. Note that all of the electrons form covalent bonds with the exception of one excess electron from the antimony or arsenic atom. This electron is free to move within the crystal, and if we were to place a battery across the crystal, the electron would race across the crystal and enter the positive terminal of the battery. Simultaneously, an electron will leave the negative terminal of the battery and enter the crystal. So we see, that by merely adding the arsenic or antimony atom and causing an impurity in the germanium or silicon crystal, we can cause *conduction* in a solid which was previously an *insulator.* The conduction is not as good as it would be in copper wire, but it is better than that of an insulator and somewhere between the two extremes. Materials of this type are called *semiconductors.* Because there is an excess electron, or negative charge, on the crystal, it is called an "N" type crystal.

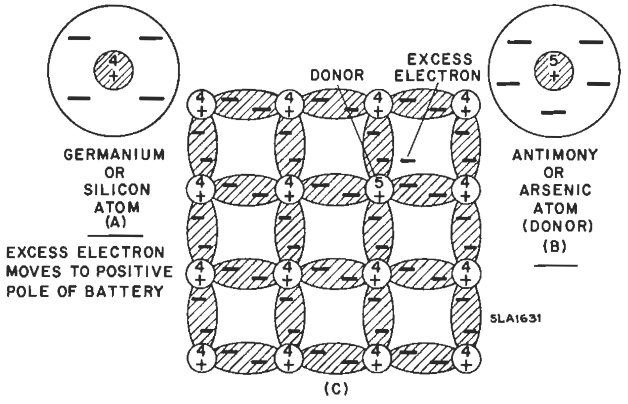


Fig. 9—Germanium or Silicon Crystal—"N" Type.

Germanium or Silicon "P" Type Crystal

Now let us see what happens when we add aluminum or gallium to germanium or silicon crystals as shown in figure 10. The aluminum or gallium atom has one less proton in its net core charge and also one less valence electron than does the germanium or silicon crystal. Therefore, one covalent bond is incomplete, and a hole is left. If a battery is applied, this hole will attract an electron from one of its neighboring germanium or silicon atoms in order to complete the four electron-pair or covalent bonds. By doing so though, it leaves a hole in another electron-pair bond. Obviously the hole will have the equivalent charge of an electron, but it will be positive. At this point, we can conclude that the aluminum or gallium atom intaking an extra valence electron acted as an "Acceptor" and resulted in a positively charged crystal. It logically follows that a germanium or silicon crystal with Acceptor impurities would be termed a "P" type crystal because of the positive charges, resulting from the holes. It also will become a semi-conductor. Each hole or positive charge is actually free to move throughout the crystal, and if a battery were placed across the crystal, the hole would move towards the negative terminal. An electron would then leave the negative terminal, enter the crystal, and fill the hole. Simultaneously, an electron from an electron-pair bond in the crystal and near the positive terminal of the battery would leave the crystal and enter the battery. This action will create another hole in the crystal, near the negative terminal. The cycle is repeated, and current flows within the circuit.

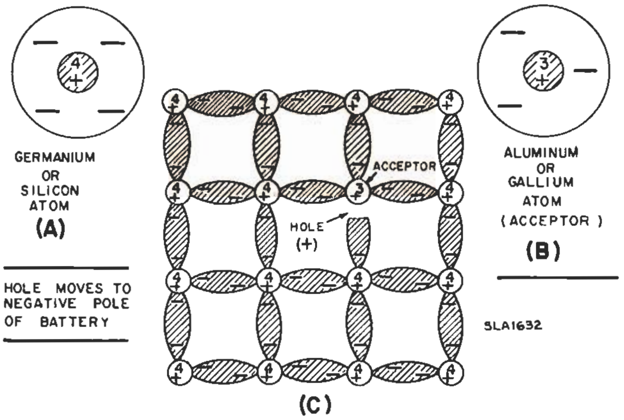


Fig. 10—Germanium or Silicon Crystal—"P" Type.

Now we see that we have two types of germanium or silicon crystals, the "N" type and the "P" type. The "N" type is formed when a donor such as arsenic or antimony joins the crystal structure. Electrons are the principle carriers of current. The "P" type crystal is formed when an acceptor such as aluminum or gallium joins the crystal structure. Here, holes, or positive charges are the principle carriers of current.

P-N JUNCTION OF CRYSTALS

Equilibrium

The theory of operation is the same for both Silicon and Germanium crystals, but since Germanium is the element most frequently used for transistors, hereafter we will refer only to Germanium in our discussion.

When two types of Germanium crystals are placed side by side, as in figure 11, the place at which they meet is called a P-N Junction. Figure 11(a) illustrates the P-N Junction in a state of equilibrium with the holes to the left of the P-type germanium and the electrons to the right of the N-type germanium. It may be expected that these holes and electrons will diffuse into each other's territory and cancel out the holes and electrons. However, the electrostatic potential distribution produced by the acceptor and donor atoms prevents this from happening. This electrostatic potential acts as though a battery were placed across the junction so that the polarity is positive to the N-type germanium and negative to the P-type. The electrostatic potential for the two types of crystal is low in the P-type and high in the N-type crystal as shown in figure 11(b). The division is spoken of as a "Hill." No current can flow through the junction unless an external voltage is applied.

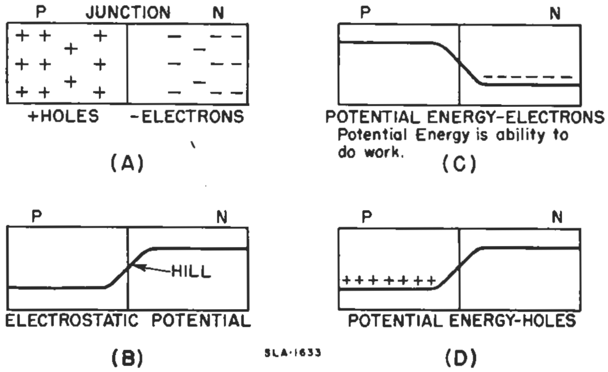
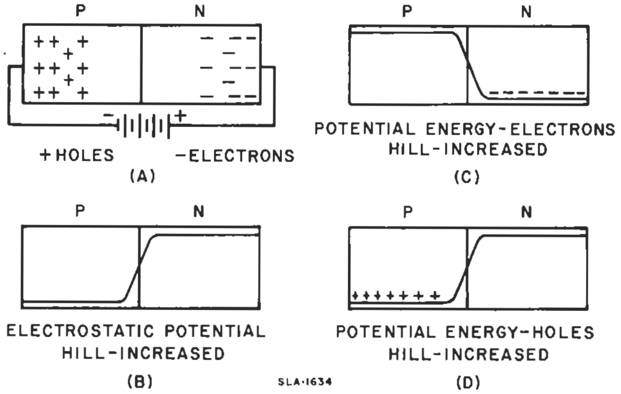


Fig. 11—P-N Junction of Crystals—State of Equilibrium.

As shown in figure 11(c) the electrons remain in the region of highest electrostatic potential, which will also be the region of minimum potential energy. Since potential energy is the ability to do work, and since the electron cannot move to do work after it reaches the highest electrostatic potential, it is obvious that it is in a region of low potential energy. The holes, being positive charges, will remain in the region of lowest electrostatic potential. This also will be the region of minimum potential energy for holes, illustrated in figure 11(d). You will note that a low potential energy region for holes, is a high potential energy region for electrons, and vice versa. Therefore, the resistance to current flow will be very high.

Reverse Bias

With a reverse bias connected as shown in figure 12(a), the holes will be pulled further to the left of the P-type germanium, and the electrons will be pulled further to the right of the N-type germanium. The electrostatic potential has, of course, been increased and the potential energy hills have also been increased. Consequently, there is even less chance for either electron or hole flow than during the original state of equilibrium. Therefore, the resistance to current flow will be very high, even higher than in the equilibrium state.



(A)

POTENTIAL ENERGY-ELECTRONS HILL-INCREASED (C)

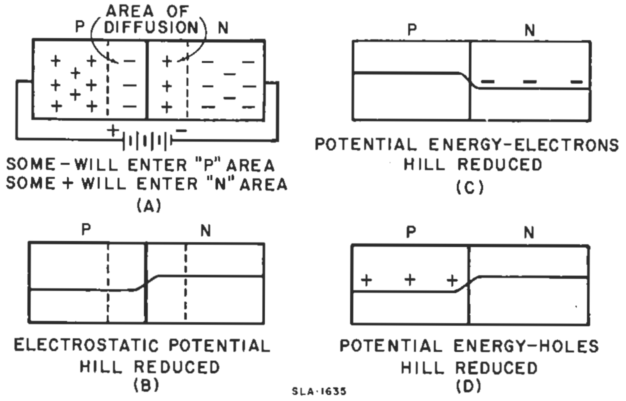
ELECTROSTATIC POTENTIAL HILL-INCREASED (B)

POTENTIAL ENERGY-HOLES HILL-INCREASED (D)

Fig. 12—P-N Junction of Crystals—Reverse Bias.

Forward Bias

Now let us consider what would happen if the battery polarity were reversed as in figure 13. The positive potential will force the holes to the right of the P-type and the negative potential will force the electrons to the left of the N-type crystal. This battery connection is called the forward bias connection and it will reduce the electrostatic potential, and at the same time will reduce the potential energy hills. The hills are actually reduced to such an extent that the electrons are able to climb the small hill and move into the P-type section, and the holes climb the small hill and move into the N-type section. Now, in a small area on each side of the P-N junction, holes and electrons combine. For each hole that combines with an electron from the N-type, an electron from an electron-pair bond near the positive terminal leaves the crystal and enters the positive terminal of the battery. This creates a new hole which flows towards the N-type germanium. Likewise, for each electron that combines with a hole, an electron enters the crystal from the negative terminal of the battery. So we conclude that the current flow in the P-section is a flow of holes, and the current flow in the N-section a flow of electrons. In this discussion, please remember the fundamental idea, "like charges repel, unlike charges attract." We can understand what would happen if a varying voltage were applied to the P-N junction. When the applied signal produces a reverse bias, the resistance is high. When it produces a forward bias, the resistance is low and conduction occurs. This then is rectification, and a much more complete description of how that old crystal detector worked.



SOME - WILL ENTER "P" AREA
SOME + WILL ENTER "N" AREA
(A)

POTENTIAL ENERGY-ELECTRONS HILL REDUCED (C)

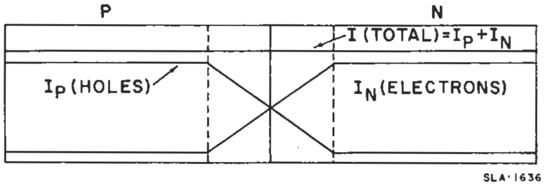
ELECTROSTATIC POTENTIAL HILL REDUCED (B)

POTENTIAL ENERGY-HOLES HILL REDUCED (D)

Fig. 13—P-N Junction of Crystals—Forward Bias.

Current Flow

Figure 14 shows the current flow we have just been talking about. Here you can see that the current flow in the P-type crystal is caused by the hole movement, and in the N-type is due to movement of electrons. Of course, the total current will be the graphic sum of the two.



1-WHEN APPLIED VOLTAGE PRODUCES A FORWARD BIAS, THE CRYSTAL ACTS AS A LOW RESISTANCE.

2-WHEN APPLIED VOLTAGE PRODUCES A REVERSE BIAS, THE CRYSTAL ACTS AS A VERY HIGH RESISTANCE.

Fig. 14—P-N Junction of Crystals—Forward Bias—Current Flow.

THE JUNCTION TRANSISTOR

Up to now, we have learned how a germanium crystal is made to conduct and have considered the effects of bias. Now, let us analyze the operation of the junction transistor. A junction transistor may be either a P-N-P junction or an N-P-N junction.

N-P-N Type—Equilibrium

Here in figure 15(a) we have a sketch of an N-P-N transistor. In (b) we see the distribution of electrons and holes for a condition of equilibrium. From our previous discussion, we recognize in (c) and (d), the displacement of donor, acceptors, holes, and electrons under a condition of equilibrium. We also expect to find the holes and electrons in a state of low potential energy and as the potential energy hills indicate, it is impossible for the holes or electrons to climb the hills and no current flow is possible.

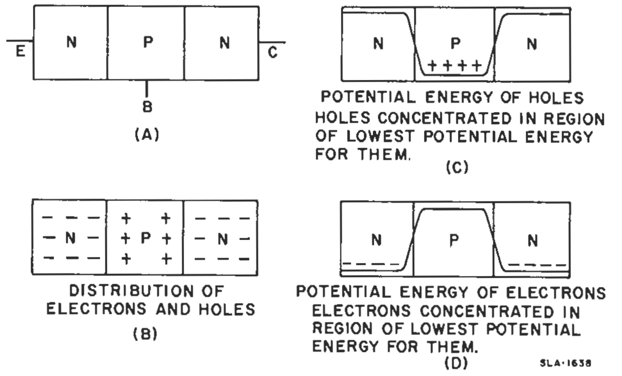


Fig. 15—N-P-N Junction Transistor—State of Equilibrium.

N-P-N Type—Signal Applied

In Figure 16(a) we note that for normal N-P-N transistor operation, the emitter is biased in the forward direction and the collector is biased in the reverse direction. Since the principle current carrier in an N-P-N transistor is the electron, we will not consider the potential hill for holes. In studying the electron potential energy hill for the left P-N junction, we know that the forward bias will, in effect, reduce the potential energy hill for this junction. This will permit some electrons to flow into the P-type germanium and since this layer is thin, most of the electrons will not combine with the holes but will pass into the right P-N junction and easily go down the right potential energy hill. This steep energy hill which favors the entrance of electrons from the base to the collector is due to the reverse bias, which is illustrated in (b).

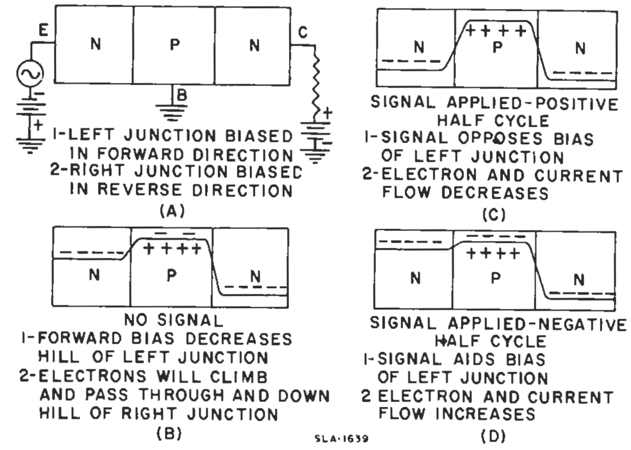


Fig. 16—N-P-N Junction Transistor—Signal Applied.

In (c) we apply a signal such that the positive half of the cycle is inserted at the emitter. This then will oppose the forward bias and the potential energy hill increase, thereby reducing the electron and current flow. Only a few electrons will then climb the left potential energy hill. Very few will combine with the holes in the P-type germanium, and the remaining electrons will slide down the right potential energy hill to the collector. Therefore, the current flow will be reduced from what it was in the state of equilibrium.

Now let's see what happens when the negative half of the cycle is applied at the emitter. In (d) we see that the left potential energy hill has been much reduced by the forward bias aided by the signal. This hill is now so small that many more electrons will easily climb it. They will pass through the P-type germanium without combining with the holes, and slide down the right hill to the collector. So we see that the current flow will then be increased over that of the equilibrium state. This then, is how a junction transistor responds to a signal.

Amplification with Junction Transistors

With the aid of figure 17, we will now investigate the transistor as an amplifier. The voltage gain is the product of the current gain and the resistance gain, as demonstrated by Ohm's Law. As you know, one important feature of a transistor is its ability to amplify, so we know that the product is greater than unity (or, one). We also know that some of the electrons from the emitter combine with holes in passing through the P-region enroute to the collector. It then stands to reason that the collector current changes are less than the emitter current changes so that the "alpha (a)" or current gain for a junction transistor is always less than

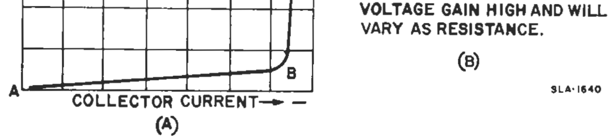


Fig. 17—Junction Transistor—Amplification.

unity (or, one). We can conclude that the resistance gain must offset this loss in current gain. We know that the collector is biased in the reverse or high resistance direction, but this is not the contributing factor, because as just explained, the electrons entering the collector slide down the potential energy hill, which in effect means low resistance.

By referring to (a), Figure 17, we see that as the collector voltage is increased, more electrons are needed to sustain this low resistance than are available. Then as the voltage is increased beyond this point (B), there is a sharp increase in the circuit resistance as the voltage keeps rising yet the current remains approximately constant. By operating on the steep portion of the curve, such as point (C), collector circuit resistances in the order of megohms are possible and we can see then, demonstrated by Ohm's law, that a transistor can amplify even though the current gain is less than unity.

It might be well to mention at this point, that in order to insure correct performance (the prevention of abnormal combining of holes and electrons) the base material must be held to a thickness of less than one-thousandth of an inch.

The same reasoning we have followed in explaining the N-P-N transistor also applies to the P-N-P transistor. The only difference is that in the P-N-P transistor, the current flow is due to hole movement, so the bias voltages must be reversed from the N-P-N type in order to obtain the forward biased condition required for operation.

THE POINT-CONTACT TRANSISTOR

Figure 18 is a sketch showing the construction of a point contact transistor. The type of germanium used can be either "N" type or "P" type, although the N-type is most frequently used. In the point contact transistor the emitter and collector contact very small areas, resulting in high resistance connections, whereas in the case of the junction transistor the contacts are low resistance soldered connections. The point-contact transistor is biased in the same manner as the junction transistor. That is, the emitter is biased in the forward direction which is low resistance, and the collector is biased in the reverse direction which is high resistance. The spacing of the point contacts is very important, usually five mils or less. We shall discuss the reason later.

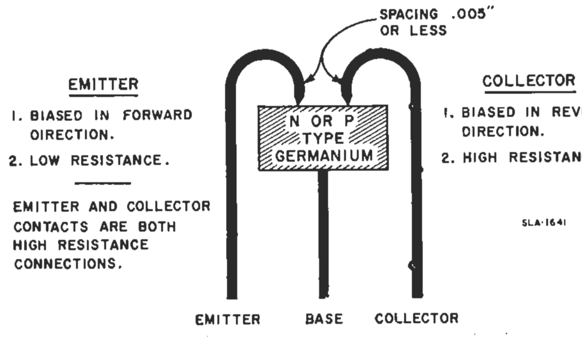
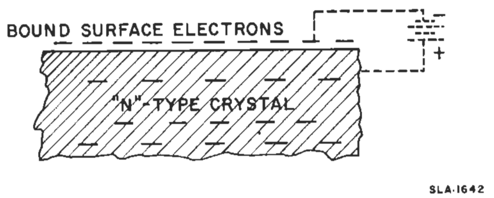


Fig. 18—The Point-Contact Transistor.

Theory

In order to study point-contact transistor operation, we must accept the Surface Status Electron theory. This theory states that electrons which find their way to the surface of a semi-conductor become held or bound in certain conditions or states, and do not readily return into the bulk of the material. For an N-type point-contact transistor, these surface electrons combine with the array of donors just below the surface to form a small potential hill as indicated by the theoretical battery shown in dotted lines of figure 19. This is similar to the P-N junction discussed earlier.



SURFACE STATUS ELECTRON THEORY.

ELECTRONS ON SURFACE OF A SEMICONDUCTOR BECOME BOUND IN CERTAIN CONDITIONS AND DO NOT READILY RETURN INTO BULK OF THE MATERIAL.

THESE ELECTRONS COMBINE WITH DONORS JUST BELOW SURFACE FORMING POTENTIAL HILL INDICATED BY DOTTED BATTERY. EQUIVALENT TO P-N JUNCTION.

Fig. 19—Point-Contact Transistor Theory.

Biasing

Figure 20 shows the point contact transistor connected with external bias batteries. As mentioned before, the emitter is biased in the forward direction and even though this bias may not exceed one volt, the point contact creates a high intensity electric field.

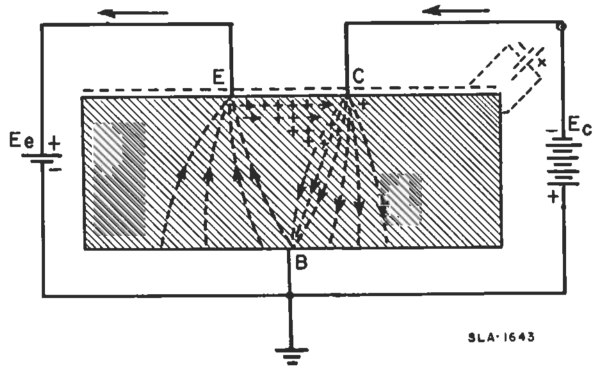


Fig. 20—The Point-Contact Transistor—Biasing.

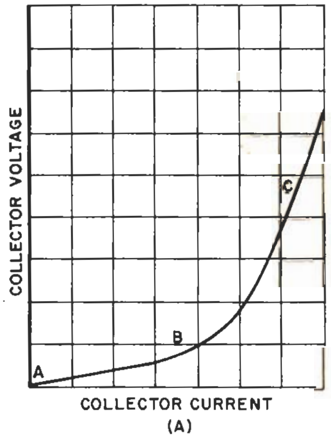
This field attracts some of the electrons from the valence bond which flow into the emitter. This in turn leaves a hole in the immediate vicinity of the emitter, and it appears as though the emitter actually injected the hole. As soon as the holes are created, they drift over to the collector under the influence of the electric field, lying between the emitter and the collector. Since the point contact transistor is made of N-type germanium, there is an excess of electrons. Consequently, many of the holes enroute to the collector combine with electrons and cease to exist. It is thus apparent that the distance between the emitter and collector cat whisker is important since too long a transit time would mean that too many holes would combine with electrons and the transistor action would be reduced. Normal spacings are up to five mils (5-thousandths of an inch). Closer spacing also allows operation at higher frequencies.

We notice that some of the holes do not follow a straight line from emitter to collector. Instead, they travel in an indirect path and form a space charge within the germanium in the region of the conducting path and thereby attract additional electrons from nearby sites. This is the reason why the circuit resistance of a point contact transistor (both forward and reverse biased conditions) is comparatively low, as compared to the junction transistor. However, the important thing to remember is that the holes reduce the collector-to-base resistance by cancelling the effect of the surface electron-donor potential hill and by attracting additional electrons. This reduction in collector circuit resistance causes a collector current flow that may be two to three times the emitter current.

In considering the collector we find that the potential hill limits the flow of electrons. Without any holes, the current flow is in the order of one or two milliamperes. However, holes that reach the collector area are attracted by the negative charge there, and in moving to the collector, tend to cancel out the potential hill. This permits more electrons to climb the potential hill, and the collector current is increased. It can now be understood how a varying signal applied to the emitter will effect corresponding changes in hole injections which in turn will result in corresponding amplifications in collector current.

Amplification with Point-Contact Transistors

As we noted in our study of junction transistors, voltage gain was the product of resistance gain and current gain. Here again, the high resistance is not due to the reverse biasing of the collector but is a function of the collector current vs collector voltage as shown in figure 21. However, this time we note that the curve is not as steep, indicating that the resistance will not be as high. This comparative loss in resistance gain is somewhat offset by an actual current gain in the point-contact transistor.



GAIN CHARACTERISTICS

CURRENT GAIN	2.5
FORWARD R	300
REVERSE R	18,000
RESISTANCE GAIN	60
VOLTAGE GAIN	150
POWER GAIN	400

AMPLIFICATION

OHMS LAW——————E=IR

CURRENT GAIN HIGHER THAN UNITY

RESISTANCE GAIN LOW.

VOLTAGE GAIN HIGH AND VARIES WITH RESISTANCE AND CURRENT.

(B)

SLA·1644

Fig. 21—Point-Contact Transistor—Amplification.

We also see that the voltage is proportional to the current, in accordance with Ohm's law, for a portion of the curve. If the applied collector bias is increased beyond a certain point, the available electrons soon become inadequate to sustain this Ohm's law relationship without the rapid rise in resistance indicated by point B on the curve. By operating in the upper portion of this curve, we obtain the required resistance gain, but as pointed out before, this gain will only approximate 60, which is well under the resistance gain for the junction transistor which we previously noted to be 2000 or higher. However, offsetting this somewhat is the current gain, which in the point contact transistor is above unity. Thus the actual voltage gain will be in the order of 150.

JUNCTION TRANSISTOR MANUFACTURE

There are two methods of making junction transistors. The first is by alloying the junctions. To do this, the three pieces of crystal are held by a mold and heated in a special furnace. The alloying can be achieved by an exact controlling of the time and temperature of the process. This type of transistor is illustrated in figure 22(a). Another method used in the making of junction transistors is to grow the transistor as a single crystal by switching the type of impurity "doping" the melt, for a few moments, so as to introduce a thin layer of opposite type of germanium. This is shown in 22(b).

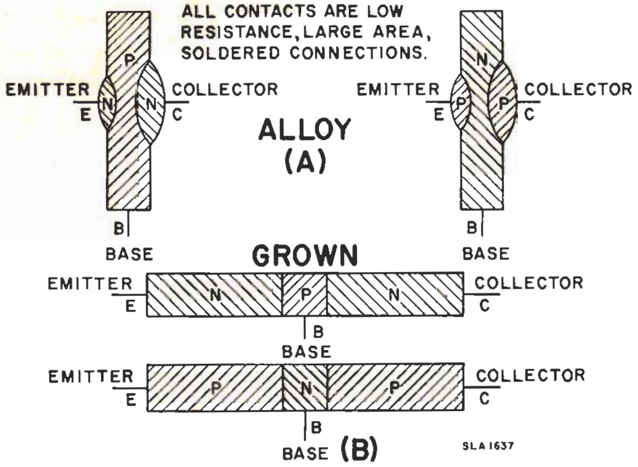


Fig. 22—Methods of Making Junction Transistors.

The lead brought out from the center strip of crystal is called the base. The lead brought out from the wafer or strip on one side of this center strip is called the emitter; and from the other side, the collector. These leads are connected through large area, low resistance, soldered contacts.

The bulk of the germanium used in making crystals is obtained from coal ash. Almost every mineral bears a trace of germanium, but there is no rich source known. It is believed that enough germanium is readily available to supply all electronic requirements for a long time.

Germanium dioxide powder is reduced to elementary germanium in a hydrogen gas furnace (figure 23), operating at 650 degrees Centigrade. After reduction, the temperature is raised to 950 degrees in order to melt the germanium. It is then cooled and comes from the furnace in the form of a silvery-grey ingot. This ingot will have impurities of about one part in 10,000,000 which is still too conductive for transistors. The impurities can be removed by slowly melting the ingot from one end to the other. The impurities stay in the molten portion of the ingot, ending up at one end of the bar. This is then cut off, and the process repeated as many times as necessary to obtain a purity ratio of one foreign atom for each billion atoms of germanium.

Growing a Single Crystal

The ingot is now pure germanium and in the state ready to introduce the right impurities that will make a transistor. In this pure form, germanium is polycrystalline; that is, the ingot is composed of many individual germanium crystals. The boundaries between these crystals are at random angles to each other, therefore, they are of no use in the making of transistors. The desired form is that of a single crystal, in which the atoms are all arranged in orderly rows and columns.

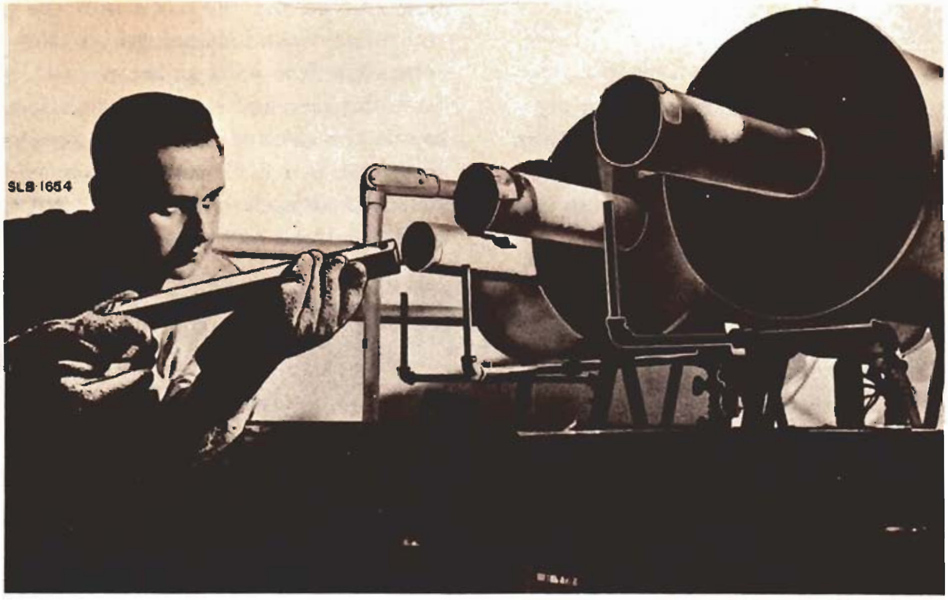
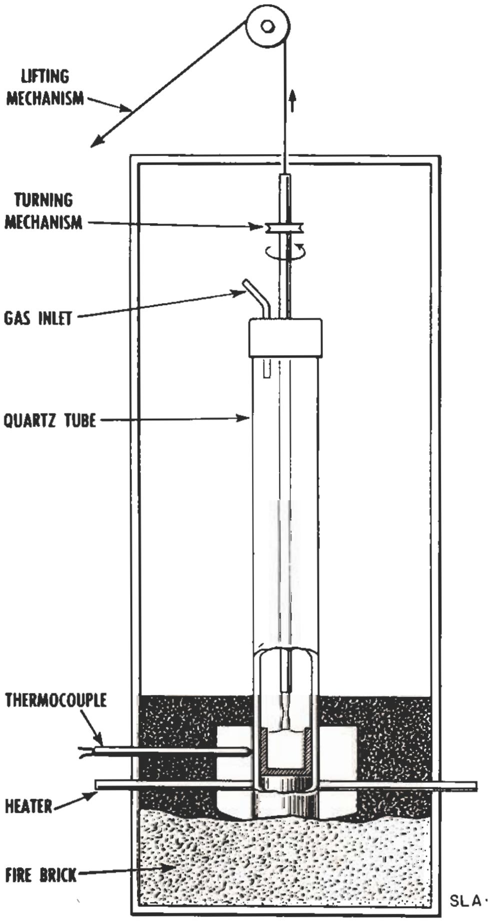


Fig. 23—Hydrogen Gas Furnace Used in Processing Germanium.

Figure 24 shows one type of apparatus for introducing the correct amount and type of impurity as well as growing the single crystal with the same crystal orientation as the seed. A small crystal "seed" is dipped into molten germanium and is slowly raised and turned. The molten germanium freezes to the seed in the same orientation as the crystal in the seed, and after several hours of slow withdrawal a long single crystal designed for transistor usage is formed.



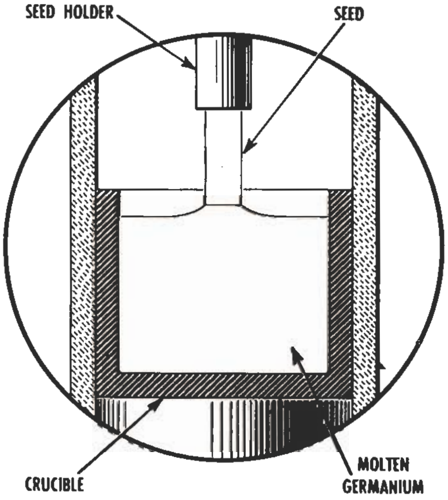
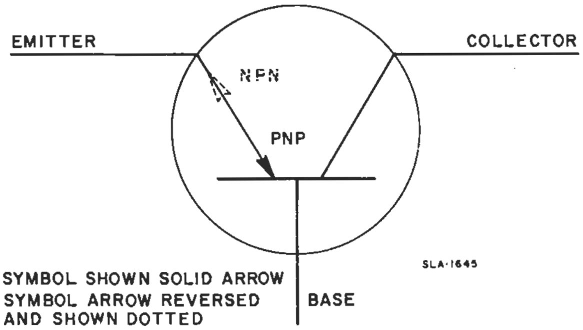


Fig. 24—Method of "Growing" a Germanium Crystal.

Figure 25 shows a single crystal of germanium. It is comparatively small, yet there is enough germanium in this crystal to make approximately 7000 transistors. The ratio of impurity in this crystal is one part to one hundred million.

The transistor symbol used in the making of circuit diagrams is shown in Figure 26. The line towards the bottom of the circle is used to represent the base connection. This is somewhat analogous to the grid of a vacuum tube. The line drawn at an angle from the base and leaving the circle near the top at the right is the collector, and is analogous to the plate of a vacuum tube. The line with an arrow head, drawn at an angle from the base, and leaving the circle at the left near the top is the emitter. As shown by the solid arrow the transistor is a PNP type. However, should the arrow be reversed as shown by the dotted portion, the transistor would be an NPN type.



PNP SYMBOL SHOWN SOLID ARROW
NPN SYMBOL ARROW REVERSED
AND SHOWN DOTTED

Fig. 26—The Transistor Schematic Symbol.

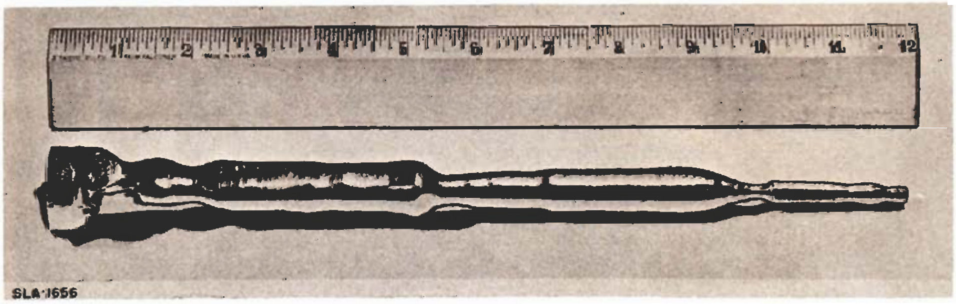


Fig. 25—A Single Crystal of Germanium—Enough for Making 7000 Transistors.

COMPARISON OF TRANSISTOR AND TUBE CIRCUITRY

Unlike the vacuum tube, a transistor does not have isolated input and output circuits. The output impedance is dependent on the input impedance, and vice versa. Also, the impedance of the transistor output is affected by the impedance of the input signal source. Therefore, a transistor becomes a valuable tool for use in matching. By carefully choosing the method of using the transistor, and the voltage used, almost any impedance ratio can be inserted into the circuitry.

In general, the emitter of a transistor can be likened to the cathode of a vacuum tube. It is the source of current flow. The base, more or less controlling the flow over the hills, is comparable to the grid of the vacuum tube. As the collector is the part of the transistor through which the current flows from the unit, it can be considered as serving the same function as the vacuum tube plate.

In Figure 27 we see the analogous circuits for the different methods of using transistors as compared to vacuum tubes.

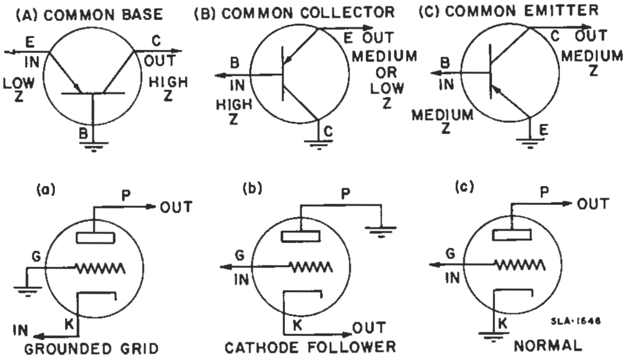


Fig. 27—Basic Circuit Comparison—Transistors vs Tubes.

(A) shows the use of a transistor with a common base connection. Frequently such a connection is spoken of as the grounded base connection, but the use of the word "Common" more nearly describes the actual use of the connection. Even though the connection is common, it will not always be grounded. This also applies to the other elements. The "common Base" connection is analogous to the grounded grid connection of a vacuum tube as shown in Figure 27(a). When a transistor is used in this way, the input impedance is low and the output impedance is high.

(B) shows the transistor connected in a common collector circuit which allows a high impedance input with a medium or low impedance output and is comparable to a vacuum tube used as a cathode follower, shown in (b). Actually a cathode follower tube circuit would not have the plate grounded. It is shown grounded here merely for comparison.

(C) indicates the connections for a transistor with a common emitter connection as is analogous to a vacuum tube connected as it is generally used. When used this way, the transistor has a medium input impedance and a medium output impedance.

Simple Transistor Amplifier

Figure 28 shows a single stage amplifier that can be used as a preamplifier for a microphone or phonograph pickup with a medium impedance, and feeding into the grid circuit of a normal audio amplifier. Notice that the circuit is simple and has few components.

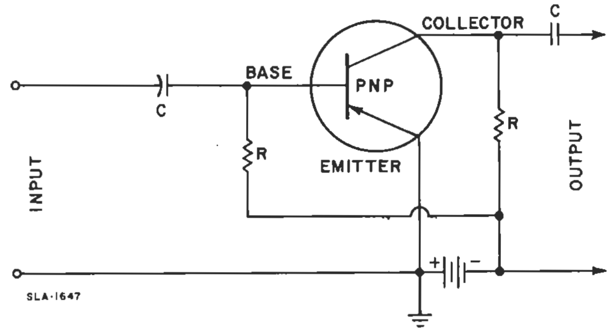


Fig. 28—Schematic Diagram—Simple Transistor Amplifier—Common Emitter Connection.

This is one reason that transistors are so well adapted to printed circuitry. We use a transistor in our High Fidelity model 6HF1 and 7HF2 instruments for several advantages which it provides: we need to match a low impedance moving coil pickup to the grid of an audio amplifier; because of the low output of a pickup such as this, we must have very high gain; and, because of the high gain needed, we must have a circuit that has practically no hum. The transistor meets all of these requirements.

Two Stage Audio Amplifier

Figure 29 is a schematic of a two stage amplifier. Again you can see how few components are used and how convenient such a circuit would be for printed circuit assemblies.

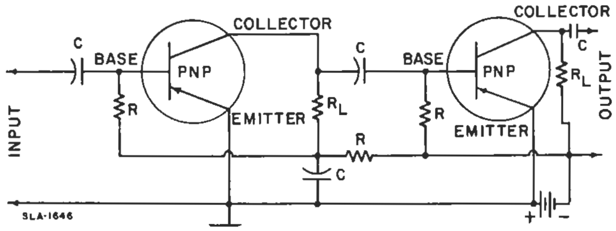


Fig. 29—Schematic Diagram—Two-Stage Transistor Audio Amplifier.

Push-Pull Amplifier

In figure 30 we see how simple a push-pull amplifier can be made. Again the components are few, and the amplifier is adaptable to printed circuit design. In this case all the transistors are of the same type crystal, and you will note that PNP_2 is used as a phase inverter. Therefore, in this case the design resembles the standard push-pull vacuum tube amplifier.

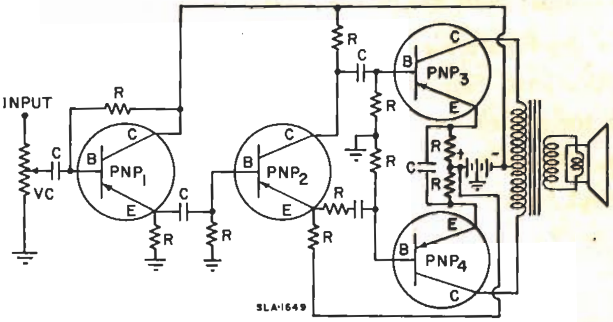


Fig. 30—Schematic Diagram—Push-Pull Transistor Audio Amplifier.

Single-Ended Push-Pull Amplifier

Figure 31 illustrates something that cannot be done with a vacuum tube. Notice that both inputs are in parallel, and both outputs are in parallel, yet we have a push-pull circuit. This is because one transistor is a PNP type and the other an NPN type. You will remember that earlier we covered the operation of the two types and found that they were opposite in performance. Therefore, if the transistors are correctly biased, that is, the PNP biased in the opposite direction from the NPN, the one type will amplify during one half the cycle, and the other type will amplify during the other half cycle. Therefore, we have a push-pull amplifier without the necessity for a transformer in either the input or the output circuits.

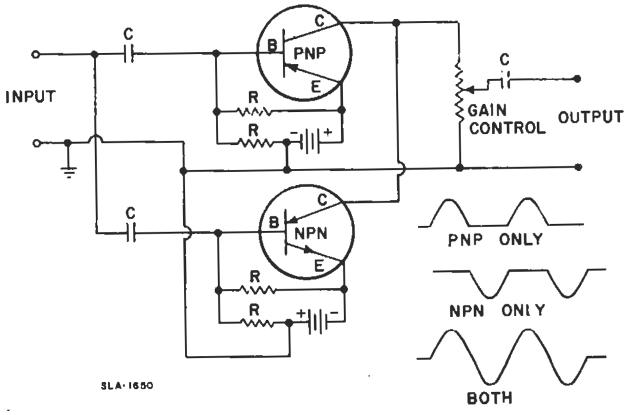


Fig. 31—Schematic Diagram—Single-Ended Push-Pull Transistor Audio Amplifier.

Push-Pull-Parallel Amplifier

Figure 32 is an expanded circuit based on the circuit described in figure 31. Here we have one push-pull pair of PNP-NPN types which are directly coupled to another pair. The outputs are then tied together. No transformers are required, and very few components. The output impedance directly matches that of the speaker voice coil, an ideal layout for a printed circuit amplifier.

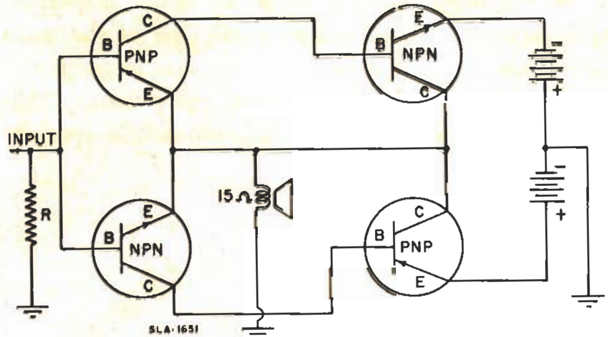


Fig. 32—Schematic Diagram—Push-Pull-Parallel Transistor Audio Amplifier.

Figure 33 illustrates the compactness and small size of amplifiers designed with transistors. This complete push-pull-parallel amplifier stage may be plugged into a single vacuum tube stocket.

Fig. 33—A Push-Pull-Parallel Transistorized Audio Amplifier.

TRANSISTORIZED EQUIPMENT

Figure 34 shows a number of small electronic instruments employing transistors in their amplifier circuits. They are equal in performance to the larger, tube-powered instruments, but are smaller in size and lighter in weight. Because of the low power consumption, it has been possible to make many important simplifications in these instruments. One of the main simplifications is the elimination of the large power supply, required by vacuum tube equipment. This makes it possible to operate the automobile receiver directly from the six or twelve volt storage battery, with no vibrator or filter system. Only a small dry cell is required in the other equipments. In most cases these provide approximately the same operating life as the normal shelf life of the battery.

In the future we will see transistors used for many applications. Some of them, of course, will be in services for which vacuum tubes have been used in the past. Others will be in services for which tubes have not yet been found adaptable.

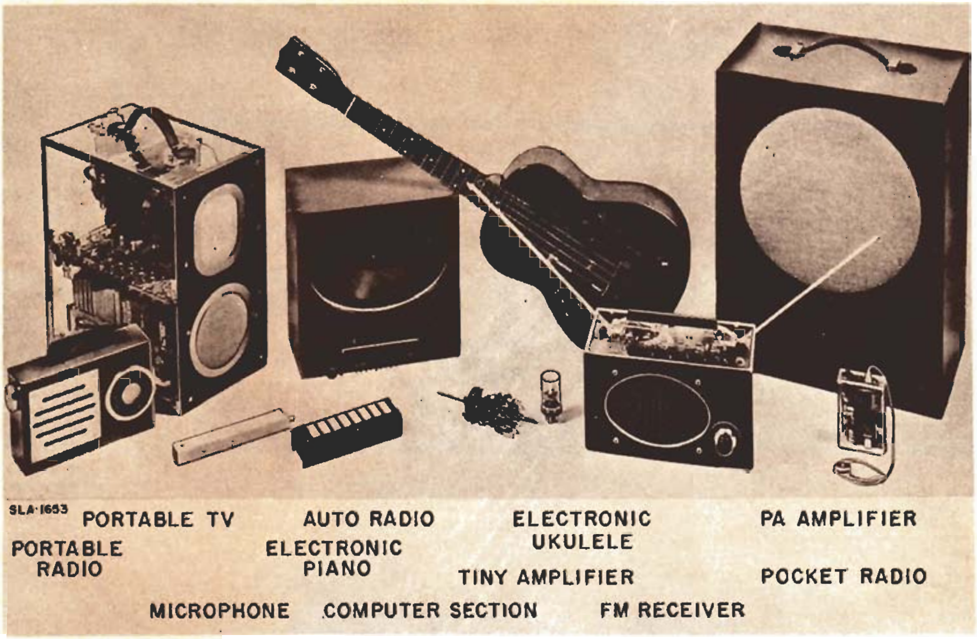


Fig. 34—Transistorized Equipment.

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