Transistor Action

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The physical principles underlying transistor action are discussed, and the basis of operation for a number of junction devices reviewed. No mathematics is required to understand this intuitive explanation.

Transistors are now so common that engineers and radio hobbyists are beginning to make wide use of them in audio applications. If the designer of transistor circuits is to be anything more than a "tinker" he will want to know something about the physical principles underlying the devices he is using. While it is true that good circuit design can be done by using the "black box" technique, in which the actual device is replaced by an equivalent circuit for computational purposes, nevertheless the astute engineer can make better use of physical transistors if he has a clear understanding of the physical principles involved in transistor action.

Much literature is available for those readers with considerable mathematical training; however a clear and simple explanation of transistor action in intuitive terms is not available. Either such explanations bring in much extraneous material and bore the reader, or else skip over the important parts, or else arrange the material in a fashion which prevents the reader from seeing similarities in the various junction devices, which similarities can be used to advantage in the explanation. No good intuitive explanation of junction transistor action is available.

This article has, I hope, hit a mean between too much background material and too little, and has arranged the explanations in such a way that similarities between various junction devices become immediately apparent. In connection with the former statement, the author assumes that the reader has some intellectual awareness (not an unwarranted assumption for the readers of AUDIO) and is not unwilling to accept some of the preliminary statements concerning modern physical theories without proof. If the reader has had some experience with transistors, so much the better. And if he has made an attempt in the past to understand transistor action, also so much the better.

Part I—Physical Fundamentals

With this short introduction, we can proceed to the business at hand. The article is divided into seven sections, which should be read sequentially. At the end of each section is a short review of the important points covered.

It should not astound the reader to find that modern physicists believe all matter to be made of "atoms," each composed of a central body, the "nucleus," and one or more "electrons" which may be thought of for the purposes at hand as revolving around the nucleus. Each electron has associated with it a negative charge of value denoted by "*e*." The atom as a whole is electrically neutral, the nucleus having a positive charge of *e* times the number of electrons revolving around it.

It will simplify our explanation if we consider the electrons in any atom divided into two categories: "bound electrons" and "valence electrons." It is the valence electrons, ranging in number from zero up through seven, that determine some of the chemical properties of elements.

A group of atoms of the same kind (that is, the same number of electrons in each atom) forms material that is known as a single "element." Hydrogen and oxygen are examples of elements. In addition, atoms can combine with atoms of other elements in certain ways to make "molecules" which in turn form material that is known as a "compound," to distinguish it from an element.

Material present in the world is often classified generally speaking as "solid," "liquid," or "gaseous." One important type of solid is known as a "crystal." Crystalline substances are characterized by the fact that their individual atoms or molecules are arranged in a definite mathematical pattern. The forces which act to hold together a crystal are exceedingly strong. One such force arises from the "covalent bond," which is a configuration of two valence electrons, one from each of two atoms, between which the bond is located. This configuration happens to be quite stable. Note that two electrons are required to form this bond.

With respect to electrical conduction properties, solids can be classified as either "conductors," "insulators," or "semiconductors," with surprisingly little ambiguity. In conductors, the valence electrons are quite free to move about the material without much opposing force. On the other hand, in insulators, the electrons are *not* free to move about, hence cannot flow to form a current. Typical conductors are copper, silver, aluminum, brass, etc., including most other metals. Typical insulators are wood, paper, mica, glass, cloth, etc. An example of a semiconductor, of which there are many known, is crystalline germanium. In order to explain semiconduction further, we'll look at the germanium crystal structure.

Germanium is the most-used material for making junction devices. A germanium atom has four valence electrons. It can form a stable crystal structure by forming four covalent bonds with its four neighboring atoms. The configuration, that is the crystal lattice, is in three-dimensional space, and is known as the diamond structure, because crystalline diamond has the same form. Often the structure is represented in two-dimensional space by rows and columns of germanium atoms, as in *Fig.* 1. Since the three-dimensional distribution of atoms is quite hard to picture, we will not attempt to draw it here.

Since all four valence electrons are used up, there is none left over to contribute toward a conduction current. Thus one might at first think that crystalline germanium is an insulator. However, two means exist to produce current-carrying, or "conduction," electrons within a sample of germanium crystal. First, thermal agitation of the atoms[1] can at room temperature be sufficient to knock a few electrons out of their covalent bonds. Not many, but a few. This situation is shown diagrammatically in *Fig.* 2. And in addition, if the specimen is illuminated with light[2], the light energy of the photons can disrupt a normal covalent bond. These two means of producing conduction electrons prevent crystalline germanium from being an insulator.

Now let's think about what happens to the conduction electron and the bond it left. The electron may merely drift away through the material. Since the

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[1] Remember that, when viewing things from an atomic level, temperature is merely a measure of the rate at which particles are "bouncing around"—the higher the temperature, the faster the atoms, which can move somewhat within their specified position in the crystal lattice, jiggle around.

[2] Remember that ordinary light can be thought of as little packages, or "photons," of energy.

covalent bonds in the lattice can accommodate only two electrons, it cannot become a permanent fixture at any one spot in the lattice. Or else it may immediately fall back into the bond it left. In general, the electron is removed with such energy that it drifts away from the spot where it was. The bond, on the other hand, is now lacking an electron. A bond in this state is called a "hole." A surprising feature of the lattice is that this hole can move in roughly the same fashion as an excess electron. Its movement, of course, consists of having an electron from a nearby bond jump into the original bond, thus moving the hole to the spot where the electron came from. The hole, being the lack of an electron, possesses a positive charge equal to *e*. For the purposes of transistor physics, the hole may be thought of as a particle with a positive charge *e*, and with characteristics similar to those of a conduction electron.

A hole can re-combine with an electron by the simple process of coming close enough so that their electric attraction will cause the electron to "fall into the hole," to put it crudely. Sometimes this process is accompanied by a release of energy in the form of a photon; more often it is not. (Of course if the hole and electron could not recombine, the crystal would eventually fall apart from lack of covalent bonds. Needless to say, this doesn't happen.)

Since the concept of the hole as a current carrier is paramount in the discussion that follows, the reader should fix in his mind the following facts about the hole: (1) It may be created by somehow drawing an electron away from the covalent bond, (2) It and an accompanying electron may be simultaneously created by thermal agitation within the crystal, (3) It and an accompanying conduction electron may be created by an incident photon, (4) The hole may be considered as a positively charged particle when thinking of its current-carrying abilities, (5) A hole and a conduction electron will re-combine if they happen to meet, and (6) A flow of holes in one direction just as much constitutes current as a flow of electrons in the opposite direction.

Fig. 3. A piece of intrinsic germanium with two leads, one at either end, like a common resistor. It can be used as a small photocell.

With what we know about a germanium crystal already, we can see that a single piece of germanium, made with two leads, similar to a resistor, (see *Fig.* 3) could perhaps perform some useful functions. For example, the temperature dependence of the "intrinsic current," that formed by thermal agitation, could be utilized in making the device act as a thermometer, with a conductivity that would decrease with increasing temperature. Fortunately, more reliable and more sensitive electrical thermometers, such as thermistors, are available.

However, the device is used as a photocell. Incident light produces electron-hole pairs, which, if a voltage is applied across the device, increase the current flowing. The so-called Germanium Photoresistor (type 1N189) is an example of commercial use of photoconductivity. (Actually, for reasons which we won't go into here, n-type germanium, as described below, is used rather than intrinsic germanium in this photoresistor.)

From this section the reader should understand in an intuitive sort of way the difference between insulators, conductors, and semiconductors. He should remember that germanium forms a stable crystal lattice in which all valence electrons are used up, but that conduction particles (electrons and holes) can be formed even at room temperature by thermal agitation, and also by incident photons. Holes can be treated in much the same way as electrons—as real particles. A flow of holes in one direction just as much constitutes current as a flow of electrons in the opposite direction.

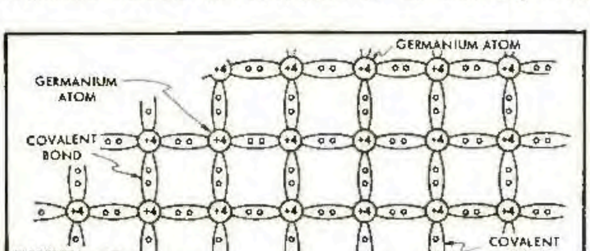
Part II—Impurities in a Germanium Crystal

The useful properties of semiconductors do not end with the pure crystals. With controlled amounts of special impurities, useful devices can be made.

Remember that in the last section we were talking about a pure sample of germanium. This was a semiconductor because the germanium had four valence electrons, all of which formed covalent bonds. If, however, one of the germanium atoms is replaced by an atom with only three valence electrons, such as indium, there will be a hole automatically formed in the lattice. The impurity atom does not break up the lattice structure—instead it fits in as well as it can, forming a hole. Of course, the crystal as a whole is still electrically neutral—the indium atom has one less positive charge in its nucleus. But nevertheless a conduction particle—namely, a hole—has been formed in a crystal which otherwise had none, except for occasional thermally or light-caused pairs. The situation is represented in *Fig.* 4.

A crystal of germanium "doped" with indium atoms (say one for every fifty million or so germanium atoms) can carry current and therefore is a better conductor than pure germanium. Because the current carriers are almost exclusively positively-charged holes, it is known as "p-type" germanium. The indium atoms are known as "acceptors" because they form bonds which accept electrons from nearby bonds, forming holes. Note that holes have been introduced without forming corresponding conduction electrons.

Similarly, a crystal can be doped with an element with five valence electrons, such as antimony, to form "n-type" germanium. The antimony atoms are called "donors" because when they fit



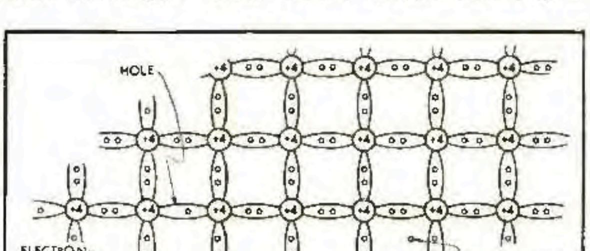
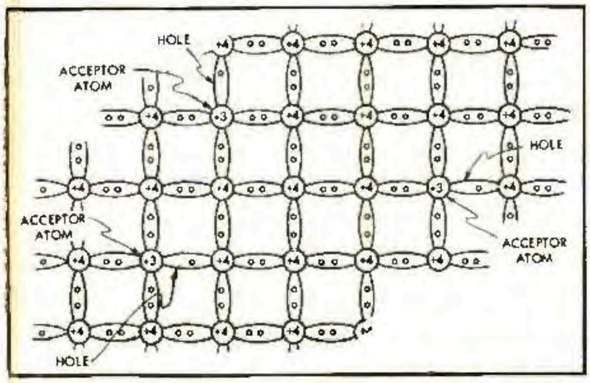


Fig. 1 (left). Representation of pure germanium crystal. Each germanium atom forms four covalent bonds with its four adjacent neighbors. Fig. 2 (right). Intrinsic germanium. Note the temperature-caused holes and electrons.



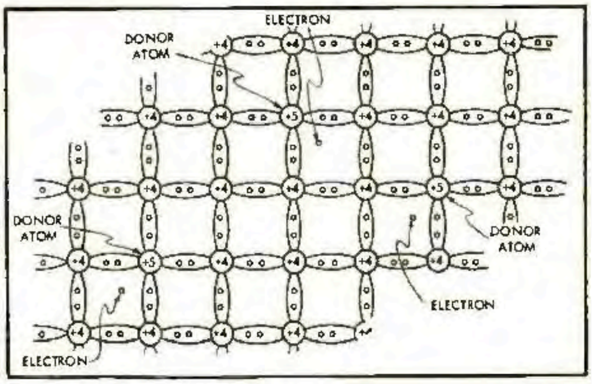


Fig. 4 (left). The addition of acceptors to otherwise pure germanium creates holes without creating excess electrons. Fig. 5 (right). The addition of donors to otherwise pure germanium creates conduction electrons without corresponding holes.

into the lattice there is an extra electron left over which is free to act as a current carrier. This is represented in *Fig. 5*. At very low temperatures (much below room temperature), the carrier introduced is attracted to the impurity atom, because they have opposite charges. However, thermal agitation shakes off these impurity carriers relatively easily.

Pure germanium, free to conduct only because of thermally-generated carrier pairs, is said to possess "intrinsic conductivity," as opposed to "n-type conductivity" (predominantly by means of excess electrons) or "p-type conductivity" (predominantly by means of holes).

The role played by the three types of germanium, p-type, n-type, and pure, is very important in transistor physics. The reader will want to remember from this section that: (1) in n-type germanium, formed by the introduction of donor atoms, the principal current-carrying particle is the electron, and the remaining donor atom in the lattice structure has a local positive charge, which however, does not succeed in "trapping" an electron and keeping it tied down at normal temperatures; (2) in p-type germanium, formed by the introduction of acceptor atoms, the principal current-carrying particle is the hole, and the remaining acceptor atoms in the lattice structure have a local negative charge, which however, does not succeed in "trapping" a hole and keeping it tied down at normal temperatures; (3) suitable juxtaposition of n-type, p-type, and intrinsic areas produces useful devices.

Part III—Action at a Junction

If we have a crystal of germanium which is half p-type and half n-type, the surface separating the two areas is known as a "p-n junction." On one side of the junction we see acceptor atoms with their local negative charge distributed throughout the area, and holes also distributed. On the other side are immovable donor atoms and many conduction electrons wandering about. Each side is at first glance electronically neutral—with equal positive and negative charge. Right near the junction there will be some diffusion of electrons and holes, with some re-combination taking place. As a result the remaining acceptor and donor atoms set up a small electric field, and the equilibrium condition of the crystal is that further diffusion of electrons and holes be stopped by a small electric field localized right at the junction.

Although the existence of this localized electric field means that the two sides of the crystal are at a slightly different electric potential, the reader should not jump to any conclusions such as that of the junction being replaced by a battery, or anything so foolish. The junction of course cannot supply power to an external resistor, and furthermore the potential difference between the two sides is a function of the temperature, and in addition can be varied by applying external power, as we shall see later.

In order to understand the rectifying action at a junction, consider the piece of crystal with a p-n junction in it, with leads attached to each end of the crystal, on either side of the junction, as shown in *Fig. 6*.

Normally, enough electrons and holes have diffused together so that quite near the junction there are no carriers (i.e. electrons or holes) present—and more carriers will not come near the junction because of the small localized electric field set up, as explained earlier. Now, if a battery is connected so that its positive terminal is connected to the p-region, and its negative terminal to the n-region, holes in the p-region will be driven away from the end of the crystal by the action of the battery, and more holes will flow into the crystal from the battery (that is, some bonds near the end of the crystal will lose one electron). Similarly, at the other end of the crystal, electrons are being driven away from the end by the action of the external battery, and more supplied to the crystal. With the externally-caused electric field in such a direction to push the holes and electrons toward each other, the crystal is said to be biased in the "forward" direction. When the electrons and holes reach the center of the crystal, they pass right through the junction, and in general travel a small ways into the other half of the crystal, whereupon they combine with carriers of opposite sign, thereby vanishing. But since more holes and electrons are continually being supplied by the battery, continued current flows through the device.

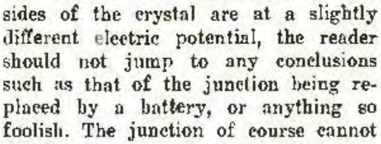


Fig. 6. A p-n junction is the surface separating p-type from n-type germanium. Here is a junction diode, using one p-n junction.

On the other hand, if the battery leads were reversed, so that the positive terminal went to the n-type germanium, and the negative terminal to the p-region, the action would be such as to draw the electrons and holes within the crystal away from each other—that is, toward the ends of the crystal. Clearly very little current can flow in this situation, since the electrons and holes cannot recombine easily.

Thus we see that this device, known as a "junction diode," can pass current easily in only one direction. The common 1N91 is an example of such a rectifier. Crystal rectifiers, made both from germanium and silicon, are in limited use already, and are expected to replace vacuum tube rectifiers in many applications as soon as the price falls a bit more.

The forward current in these devices is limited by the I^2R losses within the germanium, and also by the fact that the junction electric field never is completely eliminated by the externally-applied field. The reverse current that flows is produced mainly by imperfections in the crystal construction, or else by thermally-generated carrier pairs. If a thermally-generated pair occurs near enough to the junction so that there are no other carriers present, the hole will be attracted by the p-region, and the electron will move toward the n-region, and their motion will constitute current. And if a reversely-connected junction diode is illuminated with light, incident photons will produce carrier pairs, increasing the current. The effect is made use of in photodiodes, as explained in the next section.

The principles the reader should retain from this section are: (1) the surface between n-type and p-type material is known as a p-n junction, and a two-terminal device employing a p-n junction is known as a junction diode. (2) At thermal equilibrium with no external voltage applied, a slight electric field is set up across the junction which keeps the holes on one side and the electrons on the other. (3) If a diode is biased in the forward direction, the holes and electrons are pushed by the external power source toward the junction, near which they re-combine. (4) If a diode is biased in the reverse direction, the holes and electrons are pulled away from each other and away from the junction, so little current flows. (5) When a diode is reversely biased, any carriers, whether hole or electron, which are placed near the junction will flow toward the end of the diode.

Part IV—Some Other Junction Devices

The last statement in the last section is extremely important and is fundamental to an understanding of transistor action. "When a diode is reversely biased, any carriers, whether hole or electron, which are placed near the junction will flow toward the end of the diode." If the reader understands nothing at all from the last sections but this, he's still ready to proceed.

In the last section we described the action of a junction diode. Now let's take that same diode, and establish a reverse bias on it by connecting an external battery with its positive terminal on the n-region, and its negative terminal on the p-region. The reverse current is now due only to thermally-generated carrier pairs created in the vicinity of the junction. However, if we shine light on the junction, more hole-electron pairs will be formed, and consequently more current will flow through the device. When connected and used in this way, the device is known as a "junction photo-diode"—the 1N188 is an example of a germanium photodiode. It is possible under good conditions to achieve a yield of nearly 1—that is, one hole-electron pair for every light quantum hitting the diode. The device is thus seen to be a practical, very small, sensitive photocell.

However, illumination and thermal agitation are not the only ways to introduce holes or electrons near a reversely-biased junction. Consider the case of a three-region piece of germanium—with two p-regions at the ends, and a small, narrow n-region in the middle. See *Fig.* 7. Suppose each region is brought out to a terminal, and that between the middle and right regions a reverse bias is applied—by applying the positive terminal of a battery to the middle region, and the negative terminal to the end. Thus one junction is reversely biased. And little current will flow. Now, however, we shall connect a small battery between the middle region and the left end—this time in the forward direction. What will be the result of this connection, shown in *Fig. 8*?

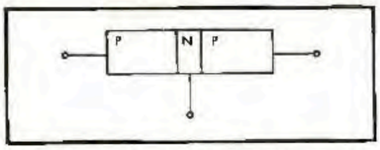


Fig. 7. A two-junction device, with each of the three regions brought out to a terminal.

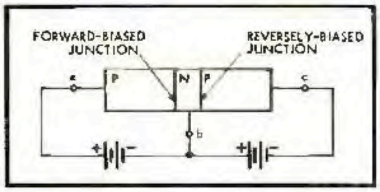


Fig. 8. Normal biasing of the p-n-p junction transistor. The emitter junction is biased forward, the collector junction backward.

At first glance, one might be tempted to treat the two junctions separately, and say that the one will remain nonconducting, and the other will conduct. However, this is not the effect observed. Instead, holes that enter the middle n-region from the forward-connected left-hand junction will see only the other junction ahead of them—and will act just like any carrier introduced in the region of a reversely-biased junction—they will flow through the junction and out the other end of the crystal. A few, to be sure, will re-combine with the electrons within the n-region, but the vast majority, especially if the n-region is thin, will proceed through both junctions and thus pass right through the crystal.

If the reader hasn't guessed it by now, the three-terminal device we have been talking about is a "p-n-p junction transistor." The end terminal which emits the holes into the middle region is known, appropriately enough, as the "emitter." The other end terminal, which collects all the holes which the emitter injects, is known as the "collector." The middle region is called the "base." The theory given above for the operation of the transistor is known as "transistor action"—the control of current through a reversely-biased junction by means of current injected near the junction by another electrode (in this case another junction).

Because of its importance let's go through it again: First, a reverse bias is set up between the base and the collector—that is, across the collector junction. The only collector current which flows (if the transistor is shielded from light) is due to thermally-generated hole-electron pairs created near the collector junction. Now, however, a forward bias is set up between the base and the emitter—that is, across the emitter junction. Thus, much current flows through the emitter. The question becomes, "what happens to the emitter current once it reaches the base?" First, a small portion of the emitter current is due to electrons which flow across the emitter junction from the base—these recombine with holes somewhere within the emitter. Secondly, some of the holes that enter the base re-combine with electrons within the base. These two together constitute the current which flows through the base lead. However, if the transistor is properly designed, the vast majority of holes pass right through the base into the collector, and serve to increase the collector current. Of course, superimposed upon the emitter current might be some sort of fluctuating signal which requires amplification.

But now the question may arise, "so what?" We just saw that the collector current is always (in the normal operating region) less than the emitter current. Is that amplification? Well, it's not too hard to see that, no matter what the collector-to-base voltage is, so long as the collector junction is biased reversely, the collector current is determined almost completely by the emitter current. In other words, a large resistor in series with the collector which changes the collector voltage when the collector current changes, will not appreciably affect the amount of the collector current, which will still be determined by the emitter current alone. Thus our input signal, at a very small voltage, can be increased to several times this voltage—in other words the transistor connected this way will amplify.

Since the base terminal is common

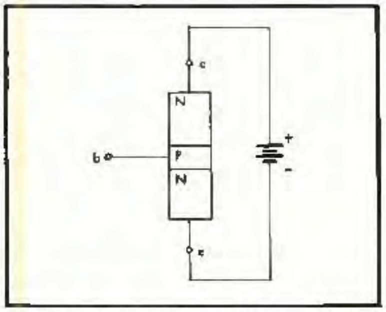


Fig. 9. Common-emitter biasing method for a p-n-p junction transistor.

to both the input and the output of the simple amplifier, it is called a common-base, or grounded-base configuration. We will see in the next section that in another configuration the device can act as a current amplifier.

This section is, of course, the most important section in the article. The sections before this merely served to introduce certain concepts used here. The following three sections will further describe transistor action, and will describe a few more commercially available junction devices of interest. Out of this section the reader should have learned: (1) A photo-diode is merely a reversely-biased diode whose current is controlled by incident light. The incident photons produce electron-hole pairs near the junction. A small, practical, sensitive photocell is the result. (2) A p-n-p junction transistor is merely a three-terminal device having two p-n junctions "back-to-back," separated by a small n-region. The collector current is determined, in the grounded-base configuration, by the emitter current only—not by the collector voltage. A small, efficient, amplifying device is seen to result. (3) Transistor action is merely the control of current through a reversely-biased junction by means of injecting proper carriers in the vicinity of the junction from another electrode.

Part V—Grounded-Emitter Operation

We saw in the last section that transistor action is merely the control of current through a reversely-biased junction by means of current from another source deposited near the junction. In a p-n-p junction transistor with the base lead common to both the collector and emitter circuits, a majority of holes coming from the emitter pass right through the base region into the collector. Since the collector current is less than the emitter current, the transistor does not amplify current, although we saw that it would amplify voltage. Let us call the fraction of emitter current which *does* reach the collector α.

α will normally be just a trifle less than one—for the sake of example, let's say that $\alpha = 0.95$. If we call the emitter current i_e, the collector current i_c, and the base current i_b, we immediately see that

$$i_c = \alpha i_e \qquad (1)$$

and

$$i_b = (1 - \alpha)\ i_e \qquad (2)$$

and therefore

$$i_c = \left(\frac{\alpha}{1-\alpha}\right) i_b = \beta\, i_b \qquad (3)$$

where β is called the "grounded-emitter current gain," and

$$\beta = \frac{\alpha}{1 - \alpha}$$

so when $\alpha = 0.95$, $\beta = 19$.

If we consider the base as the input terminal, and the collector as the output terminal, we can see from Eq. *(3)* that the collector current is many times greater than the base current, so when the transistor is operated in the grounded-emitter configuration, that is with the emitter common between the input circuit and the output circuit, current amplification takes place.

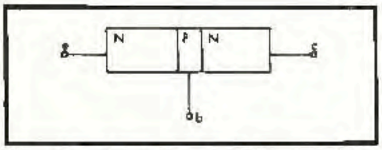


Fig. 10. An n-p-n junction transistor behaves in exactly the opposite way as a p-n-p junction transistor. All polarities are reversed.

Furthermore, by the same sort of reasoning as was employed in the last section, this current can be made to flow through a large load resistor, so voltage amplification occurs as well.

However, this mathematical derivation may not be at all convincing to the reader, so we'll go through the grounded-emitter stage again, from a physical viewpoint.

Consider the case when a battery is placed directly between the collector and the emitter, with the base left unconnected, as in *Fig.* 9. Of course, for the p-n-p junction transistor under consideration, the collector should be connected to the negative battery terminal, and the emitter to the positive. In this case, the collector junction is biased in the reverse direction. In addition, the potential of the base is slightly higher than the potential of the emitter. For if it were not, emitter current would flow, one twentieth of which would remain in the base to charge it up to the point where no more current will flow. This is the condition of the transistor for equilibrium. Now consider the case when an electron appears in the base region for one reason or another. Perhaps it was introduced in through the base lead, in which case it represents base current. The potential of the base region is lowered somewhat by the presence of the electron, with the result that the emitter injects holes into the base to try to raise its potential up to the point of equilibrium. For each electron in the hole region, the emitter injects twenty, or $1/(1-\alpha)$ holes—one of which recombines with the electron, and 19 of which flow through the base into the collector. Thus a very small amount of current through the base can control a rather large amount of current through the collector. In fact, 1 milliampere through the base can control 19 milliamperes through the collector, or $\alpha/(1-\alpha)$ milliamperes. Thus the current gain is seen again to be $\alpha/(1-\alpha)$. This is, of course, the same result we achieved two paragraphs ago by considering the device mathematically.

The reader should recognize the fact that this "transistor current multiplication" is merely another manifestation of transistor action, and is quite equivalent to the statement about transistor action made at the end of the last section.

The reader should note the following pertinent points arrived at in this section: (1) In the grounded-emitter configuration, the transistor is capable, to a first approximation, of a current gain of $\alpha/(1-\alpha)$. (2) This transistor current multiplication (often referred to as "hook multiplication") is merely another manifestation of transistor action —and thus is entirely equivalent to the former statement of transistor action.

Part VI—Other Two-Junction Devices

In this section we will discuss two more two-junction devices—both of which rely for operation on transistor action.

Besides p-n-p junction transistors, n-p-n junction transistors exist as well. See *Fig.* 10. Transistor action is exactly the same in these n-p-n units, except that all battery polarities and current directions must be reversed. For example, instead of injecting holes into the base, the n-p-n emitter injects electrons. The n-p-n transistor is exactly the same, to a first approximation, but opposite in polarity to a p-n-p transistor.

Let us consider an n-p-n transistor operating grounded-emitter—that is, with only one battery connected between the collector and the emitter, with the collector positive[3] as shown in *Fig.* 11. As a first approximation, we stated in the last section that no current would flow. As a matter of fact, however, thermally-generated electron-hole pairs will be created near the reversely-

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[3] From his knowledge of transistor action the reader should be able to verify in his own mind that the collector junction will be biased reversely with this connection.

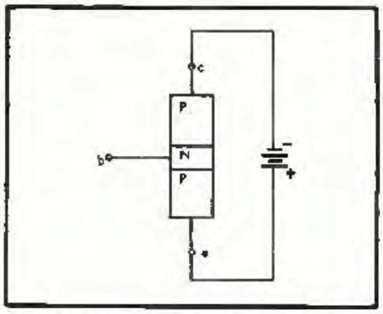

Fig. 11 A grounded-emitter n-p-n junction transistor. This is correct biasing for use as a photo-transistor.

biased collector junction, the electron of which will be pulled by the positive terminal of the battery into the collector, and the hole of which will proceed into the base. In order to counteract the presence of the hole in the base, the emitter must inject 20, or $1/(1-\alpha)$ electrons into the base, one of which will re-combine with the hole, and 19 of which will pass through into the collector. Since this is so, the collector current will be twenty times the rate of creation of carrier pairs due to thermal agitation alone. In short, the problem of thermal current in the grounded-emitter stage is greater than the problem when the transistor is fed with the base common. "Bias stabilization" under widely varying temperatures is often a severe problem—although there are techniques for reducing the effect considerably.

So hook multiplication is a problem when thermal current is considered. However, it can be used to advantage in certain cases. Consider, for example, the same n-p-n transistor with its base disconnected, and normally-biased as in *Fig.* 11, and with the reversely-biased collector junction illuminated. For every light-caused electron-hole pair formed, twenty electrons will flow through the collector circuit. Thus, in effect, the photo-diode current is multiplied by the hook multiplication ratio—$1/(1-\alpha)$. This device is known as a "photo-transistor," and is often described as a photo-diode with a built-in amplifier. Texas Instruments type 800 is typical of modern photo-transistors.

From this section the reader should retain the following points: (1) n-p-n junction transistors operate in exactly the same way as p-n-p junction transistors, except that all battery polarities are reversed. (2) Grounded-emitter transistors with the base left open-circuited exhibit hook multiplication of thermally-generated current. (3) Phototransistors use the inherent hook multiplication of transistors to advantage in producing a more sensitive photocell than the photo-diode. For some purposes they can be thought of as a photo-diode with a built-in amplifier.

Part VII—Three-Junction Devices

A device can be made which is analogous to the photo-transistor in the same way that an ordinary p-n-p junction transistor is analogous to a photodiode. For this operation, some current is injected by a fourth element placed quite near the collector junction. This element serves the same purpose as the emitter of a normal junction transistor, and so in the composite device is called the emitter. What was formerly the collector plays the role of the base, so it is now known as the base. What formerly was the emitter now becomes the collector.

The device, known as a "p-n hook transistor" is shown in *Fig.* 12. Federal Telecommunication Labs makes an experimental model, type CP-611. The device can be most easily understood by considering it connected grounded-base. In this connection, the three elements at the right (as in *Fig.* 13) form a hook multiplier—the same way that an n-p-n transistor normally would. Emitter current injected at the left passes into, and 95 per cent (or α) of it through, the base region. The portion which passes through the collector junction in the middle finds itself in what looks like the base of an n-p-n junction transistor, so biased that hook multiplication will occur. For each hole so present, 20 or $1/(1-\alpha)$ electrons will be drawn from the collector region to the far right, 19 of which will again pass through the reversely-biased junction in the middle into what is called the base of the composite hook transistor. If the base is grounded, these will flow out of the base, in which case the "collector current" will be many times the "emitter current." In fact, if the region at the left has a normal current gain of α_1, and the three elements at the right taken together have a current gain of α_2, (both less than unity), the ratio of collector current to emitter current will be $\alpha_1/(1-\alpha_2)$, or approximately β_2.

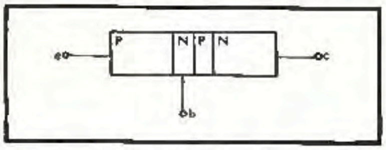

Fig. 12. A three-junction device, three of whose sections are brought out to terminals. This is the hook transistor.

Note that the base was grounded in the last discussion. The device in this configuration possesses a current gain greater than one—something which a normal junction transistor does not. It should be noted that care must be taken in designing circuits around the hook transistor, since it, like the point contact transistor, which also can have a current gain greater than 1, is unstable in certain configurations. In fact, too much resistance in the base circuit can make the device unstable.

However, Federal Telecommunication Labs reports that in their transistor, the over-all current gain from emitter to collector is very much a function of the collector current, dropping down to practically 1 for low-current operation. For this reason, circuit design problems may be less severe than otherwise expected.

Another possible device similar in form to the hook transistor may find use someday. We shall call it the hook photocell. If a hook transistor is arranged in some stable arrangement, with the base removed from ground by means of a series resistor, and then the center, reversely-biased junction is illuminated by a light source, a current multiplication will occur which is somewhat more than that due to one hook multiplication alone. Thus the device could be more sensitive than the photo-transistor. Whether a device of this sort will ever find much practical use remains to be seen, but it is mentioned here so that it may be considered a logical extension of the practical devices. The problem of a very large thermally-generated current would limit the usefulness of the hook photocell drastically.

Attempts to make a five-terminal transistor using two hook multiplications within the same crystal will probably be doomed to failure, for the injected carriers must be placed square in the middle of the middle region of the hook transistor for such a device, and the problems of building such a device out of a single crystal are quite difficult, as the reader may be able to see. This is not to say that useful five-terminal devices will not be made using junctions and transistor action—but they will probably have two or more terminals attached to one region, as present tetrode transistors and double-base diodes do.

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(*Continued on page 80*)

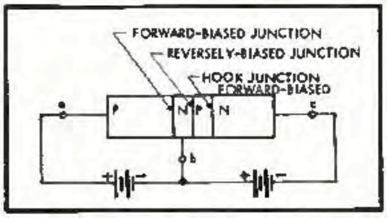
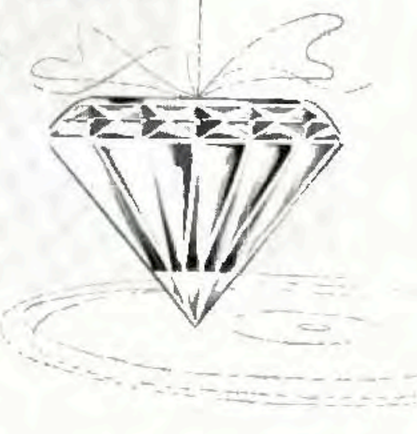


Fig. 13. Correct biasing for the hook transistor. This is the same as the p-n-p junction transistor. Only difference is that the collector has a "built-in hook mechanism."



TRANSISTOR ACTION

(from page 22)

have gathered the following information: (1) The hook transistor uses hook multiplication to multiply the collector current of an otherwise-normal transistor. In this manner an over-all current gain greater than 1 results. (2) In time a hook photocell may be developed which affords greater amplification of light-generated current than even the photo-transistor.

Summary

If the reader has been able to follow the arguments leading to an explanation of transistor action, and has followed the explanation of the various devices, he now has an intuitive feeling for the physical behavior of junction devices, which will help in designing circuitry to use these junction devices in. Described in this article were: Germanium photo-resistor, Junction diode, Junction photo-diode, Junction transistor, Junction photo-transistor, Junction hook transistor, and Hook photocell.

Various semiconductor devices were not described at all, both because of the lack of space, and because in some of these devices the exact theory of operation is not very well known. Not described at all include the following: Point-contact diode, Point-contact photocell, Point-contact transistor, Coaxial transistor, Point-junction transistor (in which one element is a point-contact and the other is a junction), Surface-barrier transistor, Field-effect transistor, Semiconductor relay, Intrinsic region junction transistor, Double-base diode, Junction tetrode, Photo-voltaic cell, Fieldistor, Symmetrical transistor, Zener reference diode, Thermistor, Photo-conductive cell, or Analog transistor.

If the reader wants to do further reading in the very interesting field of transistor action and the physical foundation of semiconductor devices, he is referred to any one of the many fine books on transistors now available, or to the three references given here, which in the author's eyes cover the field quite well. The first is now a classic explanation of transistor action.

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