HOME STUDY COURSE IN ELECTRONICS — 7

Semiconductor Devices

Semiconductor materials — germanium and silicon — intrinsic semiconductors — "doping" with impurities — "P-type" and "N-type" material — the P-N junction — the junction diode and its properties — the bipolar transistor and its operation — leakage and gain — the field-effect transistor or FET.

In the first chapter, we learned of the atomic theory of the structure of matter, and how the atoms of the various chemical elements are composed of differing numbers of electrons, protons and other particles. We saw that all atoms consist of a central nucleus of protons and other particles, around which "orbit" a number of electrons — like a miniature planetary system.

The orbiting electrons of every atom are imagined as being grouped in energy levels or "shells". In atoms of a particular element, the number of electrons in the outermost shell of each atom is of particular interest, since it determines many aspects of the behaviour of the element, both chemically and electrically. It provides the basis, in fact, for the whole discussion which follows.

Considering solid materials in general, an element will generally allow current to flow through it in the form of a passage of electrons **if it has a small number of loosely-bound electrons in its outer shell.**

Elements which exhibit this characteristic are those which we have already defined in chapter 1 as "conductors."

If, on the other hand, an element has an outer shell containing a number of electrons either near or equal to the normal maximum number (usually eight), it is generally much harder to produce a current of electrons through the material. Such elements are the "insulators," another term introduced in chapter 1.

The disinclination of insulators to support current flow may be pictured as being due to an increase in the "binding" of the outer electrons when there are close to the optimum number of them in the outer shell. The more there are, the more force must be exerted, in the form of an applied EMF, before they can be persuaded to move.

It so happens, however, that certain elements, such as germanium and silicon, exhibit electrical properties approximately midway between conductors and insulators, as well as behaving in other interesting ways.

These elements, as one might perhaps expect, have four electrons in their outer shell. They are called **semiconductors,** a name which includes not only elements but also certain chemical compounds having a similar electrical behaviour.

In a lump of a substance, the atoms or molecules of the element or compound comprising it tend to be cohesive rather than to drift apart. There are a number of different ways in which they may be "bound together" but the type of bond which concerns us here is that which occurs in the semiconductors. This type of bond is called "covalent bonding" and is represented diagramatically in figure 1.

Here the loops linking the "Si" symbols represent the outer or "valence" shells of each of 12 atoms of silicon (the inner shells of each are omitted for clarity). Note that each atom shares each of its four valence electrons (the round blobs) with the four neighbouring atoms. Thus any two adjacent atoms are effectively "sharing a pair" of electrons and each atom, in one sense, has eight electrons it its valence shell. This produces a stable bond and a disinclination to pass current.

Silicon or germanium atoms, arranged as in figure 1, in a typical pure crystal, are said to be in a "lattice," as the diagram would suggest.

As already mentioned, pure silicon or germanium having this lattice structure has a rather poor conductivity (high resistance), as all the outer shell electrons are employed in the lattice bonding and are fairly strongly bound.

If heat is applied, the added thermal energy causes the atoms and electrons to become energetic, so that a certain number of electrons are freed and made available for current flow. At low temperatures, however, the conductivity of pure silicon or germanium is poor.

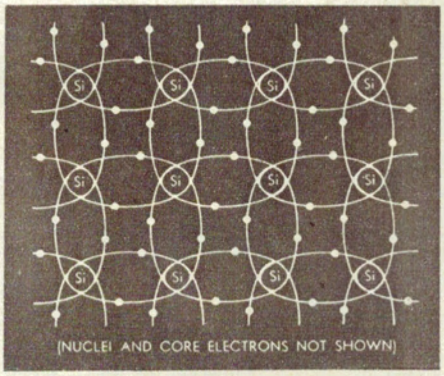


Figure 1: The silicon atoms in a piece of crystal are bound together into a "lattice" by their valence electrons.

Pure silicon and germanium are known as **intrinsic semiconductors,** because of this behaviour. The thing to remember about such intrinsic semiconductors is that they are virtually insulators at low temperatures, and only become conductors if energy is applied to their crystal lattice, for example in the form of heat (thermal energy).

If small amounts of other elements are added to the silicon or germanium as controlled "impurities", their conductivity at normal termperatures may be greatly increased. This may be made to occur in two different ways, by adding one of two groups of impurity element. This process is known as "doping" the semiconductor.

For instance, if a small amount of an element having not four, but five electrons in its outer shell (such as phosphorus, arsenic, or antimony) is added, conditions such as that shown in figure 2 may arise.

The impurity atom joins in the lattice structure and forms four covalent bonds with the surrounding atoms, but is still left with a "spare" electron. Thus this type of impurity is called "donor" impurity, as its addition results in there being free electrons available for current conduction through the crystal lattice.

Silicon or germanium crystal with a small amount of donor impurity is called **N-type** germanium, the "N" suggesting additional negative charges. Semiconductor materials in general having donor impurity are known as N-type semiconductor.

The other type of impurity which may be added is one which has only three electrons in its outer shell, such as boron, aluminium, gallium or indium. When small quantities of any such element are added to the germanium, conditions such as those shown in figure 3 appear in the lattice.

Here again the impurity atom joins in the lattice structure, but in this case it is only able to enter into covalent bonding with three of the surrounding atoms. There is no fourth electron to share with the remaining atom, so a defect in the form of an electron vacancy or **hole** is set up.

It happens that such holes are able to "travel"

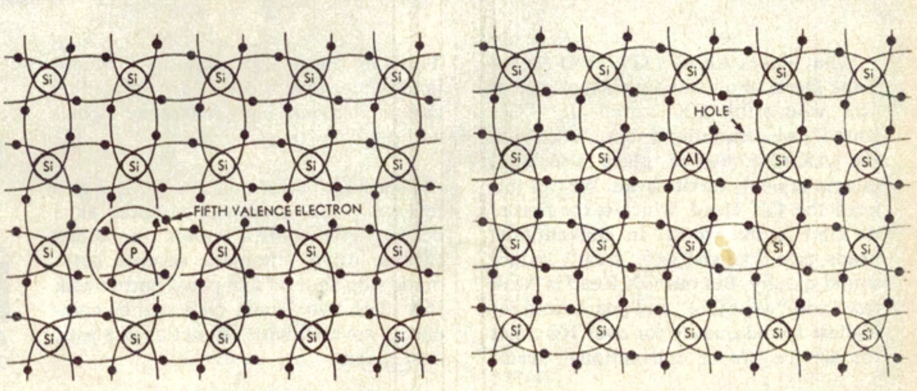


Figure 2 (left), and figure 3 (right): The effects of adding to the crystal "impurities" having either 5 or 3 valence electrons.

through the lattice from atom to atom, in much the same way as the free electrons do in the N-type material. Thus, under the influence of thermal (heat) energy or light energy or the electric field of an applied EMF, they move around the lattice and effectively constitute a current of positive charges.

The type of impurity which produces holes in the lattice is termed an "acceptor" impurity for, when the hole moves away from the impurity atom, the atom is regarded as having "accepted" a fourth valency electron from the atom which then finds itself with the hole.

A semiconductor material which has been doped with an acceptor impurity is termed **P-type,** to distinguish it from N-type material by indicating that the conduction is by holes rather than electrons. While hole movement may be interpreted as movement in the opposite direction of an electron or electrons, the holes concept is a convenient and simple way of imagining the different types of conduction in N-type and P-type materials.

It is interesting to note that the impurity atoms scattered through the parent material occupy normal positions in the lattice structure, just as if they were atoms on the parent material (ie, atoms of silicon). However, the fact that the valence bond system associates each with one outer electron too few, or one too many, means that the orbiting electrons do not exactly balance the charge of the nucleus.

Thus, although the impurity atoms occupy normal positions in the lattice, they are actually atoms with an electrical charge — **ionised** atoms, in other words, or simply **ions.** Atoms of a donor impurity, having now one less than their normal outer electrons, become positive ions. Atoms of an acceptor impurity, on the other hand, having one more than their proper number of outer electrons, become negative ions.

Thus the two types of impurity semiconductor should be visualised as (1) N-type, having fixed **positively** charged donor ions in the lattice and normally equal number of "free" (for current conduction) negative electrons, and (2) P-type, having fixed **negatively** charged acceptor ions in the lattice and a normally equal number of positive holes able to conduct current by moving through the bonding system of the crystal lattice.

The presence of impurity ions in the lattice structure of, say, silicon, with the attendant "mobile" (movable) electrons or holes, greatly modifies its conductivity.

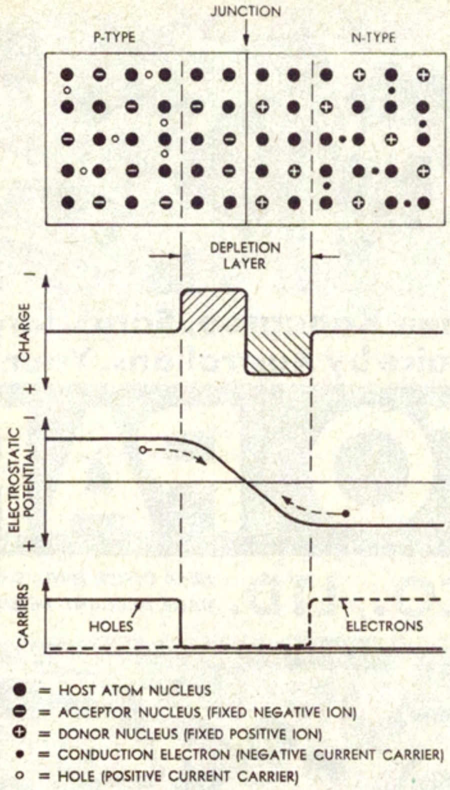


Figure 4: When P-type and N-type regions are formed adjacent to one another in a crystal, a "depletion layer" is formed.

Now let us see what happens when a crystal is arranged so that an area of P-type and an area of N-type are next to one another. Such a state of affairs is shown in figure 4, which is a diagram representing what we can now call a **P-N junction** — simply a junction between a P-type and an N-type lattice. As we shall see, such a junction behaves in a very similar way to the thermionic diode valve which we examined in the last chapter, and thus is used as the basis of the semiconductor **junction diode.**

At normal temperatures, due to thermal energy, the current carriers — electrons in the N-type, holes in the P-type — wander freely throughout the lattice. Some may wander across the junction in the course of their travels.

If a current carrier from one side wanders across the junction, there is a good chance that it will meet a carrier of the other type, each neutralising the other. For instance, if a conduction electron from the N-type side wanders into the P-type, it may easily meet a hole and "fill" it, the lattice in that immediate region reverting to normal. Similarly, when a hole appears in the N-type region, there is a very good chance that it will meet a conduction electron and the two will cancel one another as before.

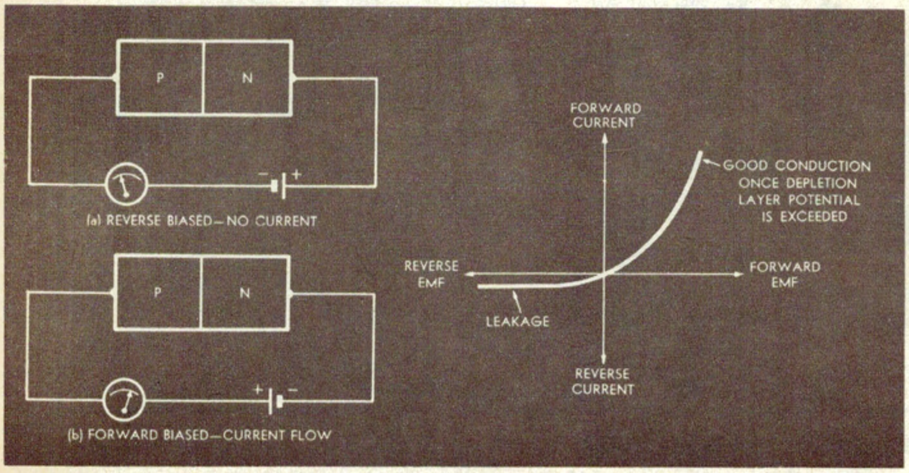


Figure 5 (left), figure 6 (right): Because of the behaviour of the depletion layer, a P-N junction acts as a "one-way" conductor.

Due to this mutually neutralising action, at normal temperatures there is a section of the crystal immediately surrounding the junction which has virtually no carriers. This is called the **depletion layer,** signifying that it is effectively a "no-man's land" as far as free current carriers are concerned.

In the P-type section of the depletion layer there are no free holes present, and there is thus a net negative charge — due to the fixed acceptor impurity ions. Similarly, the depletion layer in the N-type region acquires a net positive charge, due to the fixed donor impurity ions and the lack of free electrons.

As the small graph in figure 4 labelled "charge" shows, this means that the section of the crystal occupied by the depletion layer differs from the rest of the crystal in having nett charge "humps," one each side of the junction. There is a negative charge "hump" on the P-type side, and a positive charge "hump" on the N-type side (this is shown as a "dip" because it is of the oppositepolarity).

Because of this setting-up of opposite charge concentrations, each side of the junction, the P-type and N-type sections are effectively shifted in potential with respect to one another. For instance, the P-type region is effectively negatively-charged with respect to the N-type, because electrons in the N-type are prevented from passing to the P-type region due to the "hump" of negative charge on the far side of the depletion layer. (remember, like charges repel one another.)

The same is true of holes in the P-type region, which are discouraged from passing to the N-type region by the net positive charge N-type part of the depletion layer.

As the second curve of figure 4 shows, we can represent the potential difference which is set up by the depletion layer by showing a gradient or slope in the depletion region, with the P-type negative with respect to the N-type. Or the N-type positive with respect to the P-type, whichever you prefer.

Looking at thjs potential diagram one can see the potential "hill" that carriers would have to surmount if they were to cross the depletion layer and reach the other region. Right-way-up, the hill for electrons may be seen, travelling from right to left; inverting the page will show the hill seen by the holes.

It is the potential "hills" set up at the junction as part of the formation of the depletion layer which under normal conditions cause the layer to remain at a certain constant width, and with a certain potential difference between the P-type and N-type sections of the crystal. For a given amount of thermal energy, electrons and holes cross the junction only until they set up the depletion layer and its potential hills to an extent which discourages any further movement. A balance or **equilibrium** is thus reached, with the width of the depletion layer and the potential difference between the two sections determined at least partly by the amount of thermal energy present.

With us so far? If you're not too sure, it would be a good idea to read some of the foregoing material again, as the concepts involved are quite important.

Now if we try to pass a current through a germanium junction diode or "crystal" having a P-N-junction, by applying an EMF across its end, we find that interesting things happen. And it all depends upon the way we connect our EMF, for different things happen for each of the two possible connection polarities.

If we connect an EMF so that its positive polarity connects to the N-type region and its negative polarity to the P-type region, as in figure 5(a), we are simply increasing the potential difference which the depletion layer has already set up between the two regions. What happens is that we simply increase the width of the depletion layer (and increase the steepness of its potential difference gradient) by causing more carriers in the crystal structure to cancel.

After a very brief and tiny flow of these carriers no current flows apart from a leakage current which is due to various lattice imperfections and effects which need not worry us just at present. The initial flow amounts to a capacitive charging current, just as if the junction was a capacitor — which, in fact, it is.

In this condition, which is called **reverse biasing**, the junction may thus be regarded as an open circuit. Or more exactly, as a low value capacitor with a small leakage current.

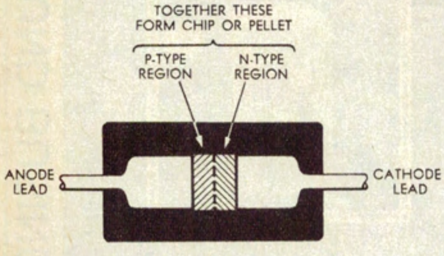


Figure 7 (above): The construction of a modern silicon rectifier diode. Figure 8 (right): The construction of a low-power glass package germanium detector diode.

If on the other hand we connect an EMF to the crystal so that its positive and negative polarities connect to the P-type and N-type regions respectively, as in figure 5(b), the situation is quite different. In this case the external EMF opposes that set up by the depletion layer, rather than assists it.

If the external EMF is greater than that of the depletion layer (which is in practice only a few hundred millivolts) there will thus be a net EMF acting in the direction of the external EMF, and the potential "hills" of the junction will be compensated by larger "downhill" sections. Current is thus able to flow, in terms of both electrons and holes within the crystal and electrons alone in the external circuit.

A junction in this condition is said to be **forward biased.** Forward biasing thus results in high conductivity (low resistance) and easy current flow.

Figure 6 shows a typical current-voltage curve for a semiconductor junction — note the low current with reverse biasing (due to leakage) and the sharp rise in current with forward biasing as the depletion layer potential is exceeded.

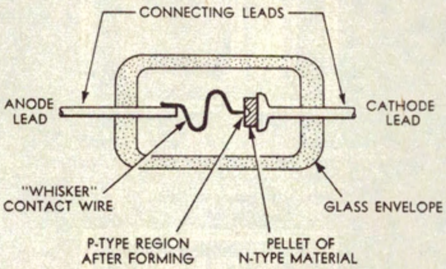
As this curve shows, the semiconductor junction is thus very similar to the diode valve which we examined in the last chapter — it is effectively a "one-way" path for conduction.

Sealed in a small glass shell or plastic or metal package for moisture protection, and fitted with two connection leads, it is the familiar junction diode which is used in "crystal" sets, in radio and TV receivers for detection and other jobs, and in power supplies for rectifying AC into DC. We see some of these uses in later chapters.

Many modern silicon diodes are made with the P-type and N-type regions formed together in the same tiny "chip" of crystal, rather like the structure of figure 4. The regions are formed as part of the same crystal structure either by a controlled doping process when the crystal is being grown, or by growing a crystal which is uniformly doped with one type of impurity, and then changing certain areas into the other type of material by "diffusing" atoms of the opposite type of impurity into them from a surrounding vapour at high temperatures. The structure of a modern silicon diode of this type is shown in figure 7. Note that the P-type and N-type regions of the chip are merely two electrically different regions within the same physical piece of material.

In figure 8 is shown a diagram of the construction of a typical small germanium junction diode, whose construction is a little different. During construction the piece of N-type germanium is soldered to the cathode lead, and the fine wire "cat's whisker" contact welded to the anode lead so that it is in contact with the surface of the germanium. When assembly is complete, a short but heavy pulse of current is fed through the device, whereupon a small amount of the wire material melts and dissolves in the germanium near the contact.

The composition of the wire and the techniques used are such that this produces a very small area of P-type germanium in the immediate vicinity of the wire contact, to which the wire is firmly welded. Thus a P-N junction is formed which is small in area — and thus low in capacitance, which is desirable for many applications — yet quite robust.



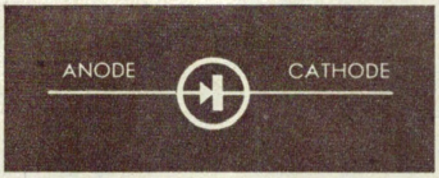


Figure 9 (above): The usual schematic circuit symbol for a diode.

The usual schematic symbol for a junction diode is shown in figure 9.

Having discussed the junction diode we can now progress to the bipolar transistor. This is simply the junction diode carried one step further — a semiconductor crystal having not one but two P-N junctions. They are near one another and, as we shall see, they interact in a way which makes the transistor able to amplify small signals. The bipolar transistor is thus the semiconductor version of the triode valve, in the same way that the junction diode corresponds to the diode valve.

There are two different types of bipolar transistor, as there are two different ways in which one can arrange two P-N junctions to be side by side. One type is the PNP type, where, as the letters suggest, the two junctions share a common N-type region and have separate P-type regions; the other is the NPN type, where the two junctions share a common P-type region.

Both types are quite practical and, in fact, they are often used side by side in circuits — one type being best suited for some jobs, the other type for different jobs.

Figure 10 shows a diagram of an elementary PNP transistor. The common N-type region in the centre is thin, and is called the **base** region. The left-hand P-type region which is called the **emitter** is normally forward-biased with respect to the base by means of the battery E1, so that the base-emitter junction conducts freely.

The right-hand P-type region, termed the **collector**, is biased in the opposite direction by battery E2, so that the base-collector junction is reverse-biased and would normally be considered to be a high resistance. However things are not the same as they would be with single junction.

As we mentioned before, the base region is made quite thin. It is also made weakly N-type by only doping it with small quantities of donor impurity, whereas the emitter region is made quite strongly P-type by strongly doping it with acceptor impurity.

This "differential" or unbalanced doping has one major effect: it makes holes play the major part in the current conduction of the emitter-base junction. In other words, most of the current passed by the junction is in the form of holes passing from emitter to base, rather than in the form of electrons passing in the reverse direction.

Because the base is thin, the base region part of the reverse-biased collector-base junction depletion layer extends almost to the emitter-base junction. This would not normally have much effect on the base, as the normal base carriers are electrons and would not be inclined to "climb" the potential "hill" to the negatively-charged collector. But it has quite an effect on the holes which reach the base from the emitter.

To these, the "hill" is not an uphill grade but an inviting downward slope. Thus, unless they are met and cancelled by one of the free electrons in the base as soon as they arrive, there is a good chance that they will "roll down" the potential hill into the collector region.

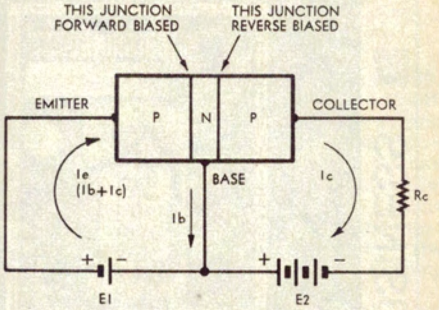


Figure 10: An elementary bipolar transistor, whose operation relies upon the interaction between two P-N junctions.

Confused? Then consider it from another viewpoint. The base-collector junction is reverse-biased, meaning that carriers would normally not pass from one side to the other because of the fixed-ion concentrations and potential "hill" of the junction depletion layer. But the "hill" is only an upward grade for the particular carriers normally present on each side.

What the emitter-base junction does, because of its forward bias, is to **inject** the "wrong sort" of carriers into the base region. Not the usual electrons, which see an upward grade to the collector region, but holes — which see the potential gradient as a downward grade, and may therefore pass straight through.

The holes "haven't been told" that the collector junction is meant to be an open circuit, as it were, and they accordingly have no objection to crossing over!

Not all of the holes which cross the emitter-base junction pass through into the collector. A few are cancelled by electrons before they can do so, and the base region accordingly receives a corresponding number of electrons from the external base connection — in other words, a small amount of the original emitter current flows "out" via the base lead, although most of it passes through to the collector.

The currents in the transistor can be visualised in terms of the base lead current Ib and the collector lead current Ic. In figure 10, Ib can be imagined as flowing in the small left-hand circuit loop, while Ic flows around the large outside loop. Ie may be considered as simply the sum of the two, as they both flow through the emitter lead.

Due to the action of the transistor, there will be a definite ratio between Ib and Ic, the collector current normally being many times Ib. It happens that if we change Ib by a small amount thereby modifying the base-emitter depletion layer, Ic will be found to change by a proportional and much greater amount.

In other words, the transistor will amplify small current changes. If we superimpose a small signal on the base current Ib, a larger replica of the signal will appear in the collector current Ic. If we include a resistor Rc in series with the collector, it will develop a voltage drop which will be proportional to the current changes, to produce an amplified output voltage.

Like the triode valve, then, the bipolar transistor can amplify tiny signals so that they may be used to perform such tasks as operate earphones, loudspeakers, television picture tubes and so on. It is thus a very useful device in many fields of electronics — particularly as it does not need to be supplied with heater current as does the triode valve.

Before we end this discussion of the bipolar transistor, there are one or two points which we should look at. The first is the matter of the amount of amplification obtained.

It should be fairly obvious from the foregoing discussion of the operation of the transistor that the amplification or gain will be governed by the number of holes which pass straight through the base from emitter to collector. The fewer the number of holes which are intercepted by electrons in the base to produce Ib, the higher will be the gain.

In manufacturing the transistor the gain can thus be manipulated by two methods: (1) making the doping ratio between the emitter and the base high so that the current is mostly holes going from emitter to base, and (2) making the base thin so that there is less opportunity for the holes to meet electrons before crossing to the collector. There are also a number of other techniques which need not concern us at present.

There are a number of ways of expressing the gain of a transistor, but many need not concern us here. For the present, it is probably sufficient to know that there are two common terms used, both expressing gain in terms of current ratios.

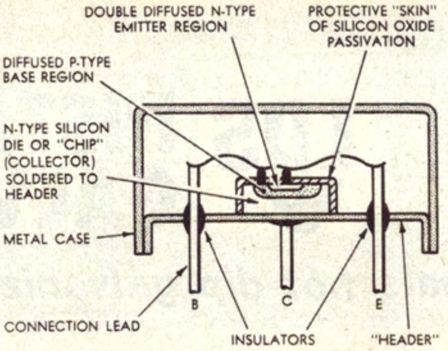


Figure 11 (above): The construction of a modern silicon planar transistor. The size of the chip has been exaggerated to show its various regions more clearly.

The first is **alpha** (α), which expresses the gain in terms of the ratio between the collector and emitter currents:

$$\alpha = Ic/Ie \tag{1}$$

Since the Ic is always less than Ie, α is always smaller than one. It is very close to one for high gain transistors, and lower for low gain transistors.

The other current gain ratio is **beta** (β), which expresses gain in terms of the ratio between collector and base currents:

$$\beta = Ic/Ib \tag{2}$$

Beta is almost always more than one, and generally much higher. Most modern transistors have a beta of between 50 and 500, although some may go as low as 20, or as high as 10,000.

Since alpha and beta are merely different expressions of the same basic effect within the transistor, knowing one always allows the other to be calculated.

$$\beta = \alpha/(1-\alpha) \tag{3}$$

and conversely

$$\alpha = \beta/(1+\beta) \tag{4}$$

It should be realised that due to thermal energy at normal ambient temperatures, some electrons and holes are generated in small quantities in all types of semiconductor — intrinsic, N-type and P-type. Thus, in the bipolar transistor, **even when an internal input current is not applied,** there are small currents flowing because thermally generated carriers "of the wrong sort" are present in small numbers and are able to cross the various junctions.

For instance, due to heat energy, there will be some holes present in the N-type base region even in the absence of holes being injected from the emitter, and these will be able to "roll down the hill" into the collector.

These thermally generated "minority carriers," as they are called, are the major reason for the small **leakage** currents which are observed to flow in the transistor even when no input is applied. As the number of minority carriers generated depends upon the temperature, the leakage currents are likewise proportional to temperature, both externally applied and internally generated. This is one of the things which tends to complicate transistor circuits.

Although in the foregoing description of bipolar transistor operation we have considered only the PNP type, the operation of the NPN type is very similar, except that the operating potentials and currents are reversed. The main difference is that the principal conduction carriers are electrons, rather than holes. The reader might find it worthwhile to trace the operation of an NPN transistor out for himself, by working through the description again and substituting electrons in place of holes.

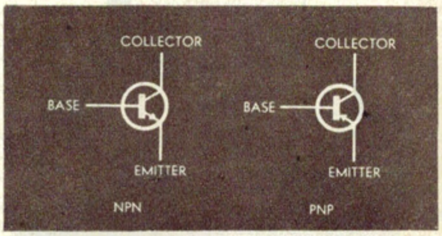


Figure 12: The usual schematic circuit symbols for bipolar transistors.

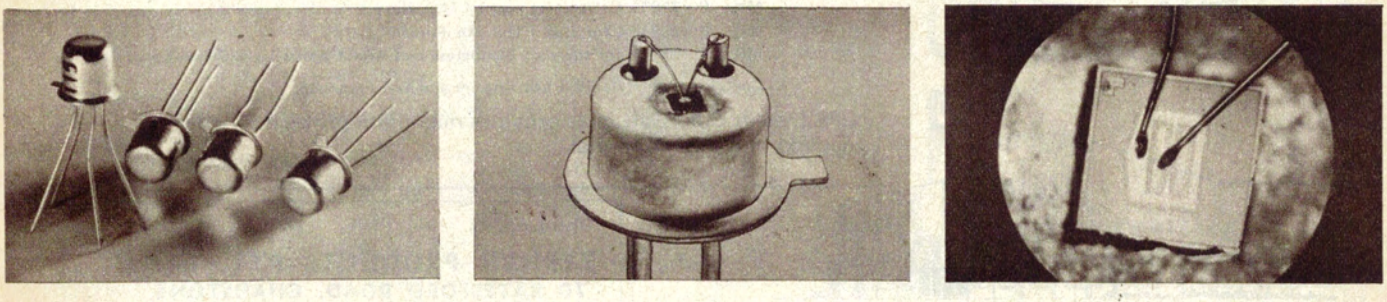
Figure 11 shows the construction of a modern silicon planar bipolar transistor, illustrating the form taken by a practical device. The collector, base and emitter regions of the transistor are formed within a single tiny chip of silicon, by the impurity diffusion process mentioned earlier.

Figure 12 shows the usual schematic symbols used to represent NPN and PNP bipolar transistors in circuits.

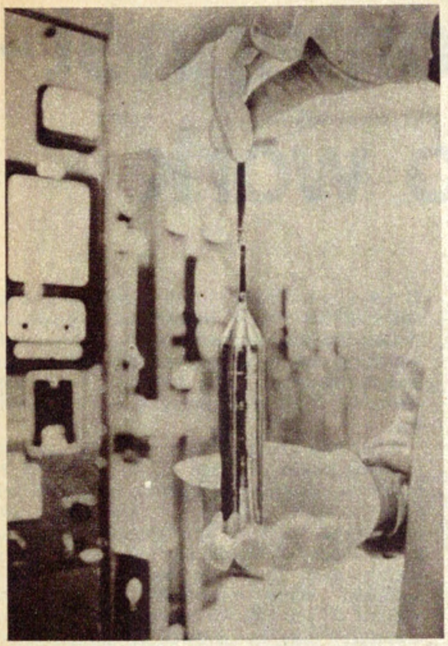
Although the bipolar transistor may be regarded as the semiconductor equivalent to the triode valve, there is one vital difference. The valve controls output (plate) current by input voltage (grid bias), and has a very high resistance input. It draws microscopic input current, if any at all. On the other hand, the bipolar transistor for its very operation must draw at least some base input current — and may hence present an input resistance as low as a few hundred ohms.

Using suitable circuit configurations it is possible to arrange for a bipolar transistor to present an effective input resistance as high as several megohms; however, in order to obtain higher figures, it is generally necessary to employ a different type of device.

Such a device is the **field-effect transistor or FET,** which consists basically of a thin "channel" region of one type of semiconductor



Three pictures which further illustrate the construction of a silicon planar transistor. At left are completed devices; in the centre, a device without its metal can; and at right, a close-up of a chip with its connection wires.



First step in the manufacture of most semiconductor devices is to grow large single crystals of pure silicon or germanium. This picture shows a single crystal of pure silicon, from which many tens of thousands of devices will be made.

material surrounded on both sides by regions of the opposite type.

Like the bipolar transistor, the FET may be made in two possible versions. It may be made in a P-channel version, consisting of a thin channel of P-type material surrounded on both sides by N-type regions; or alternatively in an N-channel version, in which the channel is of N-type material and the surrounding regions are P-type material.

The construction of an N-channel FET is shown in figure 3. It may be seen that the channel is a U-shaped region of N-type material formed into a chip of primarily P-type material. The P-type regions on each side of the channel are connected together to form the "gate" electrode of the device, while connections made to each end of the channel region form the "drain" and "source" electrodes.

The operation of the FET depends upon the fact that, as we saw earlier in this chapter, electrons and holes wandering across a P-N junction tend to neutralise one another and cause a carrier-free depletion layer to be set up on either side of the junction. Because this depletion layer region is exhausted of current carriers, it is virtually an insulating region unable to conduct current.

The P-N junctions forming the sides of the channel of a FET will have such depletion layer regions, and the depletion layers will extend into the channel. Because they are virtually insulating regions, they therefore tend to make the effective electrical width of the channel somewhat narrower than its physical width. And if an external voltage is applied between the gate and channel regions so as to reverse bias the junctions, the depletion layers will expand further into the channel to make it narrower still.

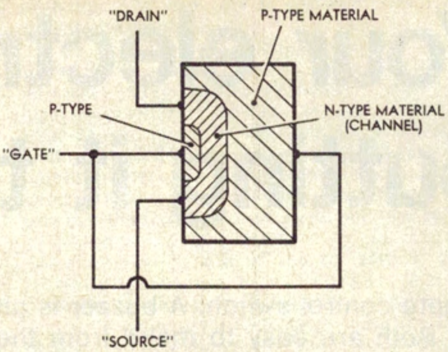


Figure 13: The basic structure of a field-effect transistor or FET, whose operation is rather like that of the triode valve.

The effect of this narrowing of the channel is to reduce its ability to conduct current between the source and drain electrodes connected to its ends. In fact, if the reverse bias connected between gate and channel is increased sufficiently, the depletion layers will extend right into the centre of the channel and meet, virtually turning the whole channel into an insulator. Naturally this effectively "blocks off" the channel as a conducting path as far as the source and drain are concerned.

If a potential is connected across the length of the channel by means of an EMF applied between drain and source, it is found that the width of the gate-channel depletion layers may be used to control the resulting current. The drain-source current may be varied simply by adjusting the reverse bias applied to the gate-channel junctions, and a relatively small change in gate bias can produce a relatively large change in drain-source current.

The FET is thus capable of amplifying small signals, in much the same way as a triode valve. In fact it is a much closer equivalent to the triode valve than the bipolar transistor, because like the valve its input control electrode — the gate — does not draw significant current. Thus the gate of the FET corresponds to the grid of the valve, while the source and drain correspond to the cathode and anode or plate respectively. This may be seen by comparing figure 14 with figure 6 in chapter 6.

Like the thermionic valve, the amplification of a FET is expressed in terms of **transconductance,** and measured in milliamps/volt. The usual schematic circuit symbols for FET devices are shown in figure 15.

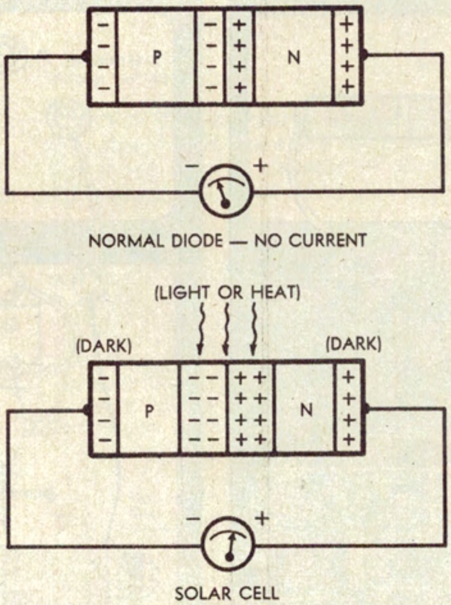


Figure 16: Diagrams used to explain the operation of the solar cell.

In passing it should perhaps be noted that the type of FET we have just described is only one of a variety of practical types. Another type which the reader may meet is the MOSFET, in which the gate and channel are insulated from one another by a thin layer of oxide.

There are many other types of semiconductor device besides those which we have looked at in this chapter, but unfortunately space does not permit dealing with these here. Happily the reader will find that the junction diode, bipolar transistor and FET devices are those which he will tend to meet most often, so that the basic grounding provided in the foregoing should be found very useful. More information on semiconductor devices in general may be found in our companion handbook, "Fundamentals of Solid State".

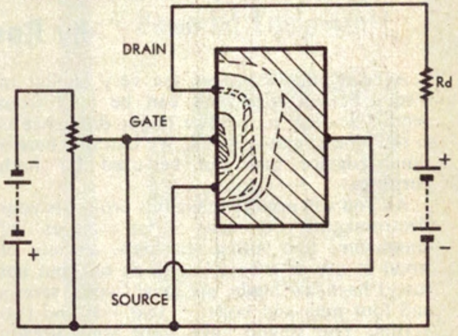


Figure 14: Because a small negative bias on the gate of a FET controls the channel current, the device can amplify.

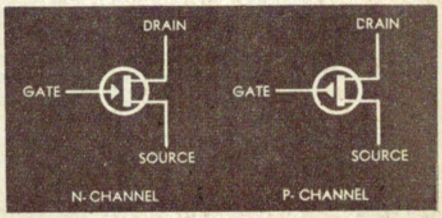


Figure 15: The usual schematic circuit symbols used for FET devices.

A final note before we leave the topic of semiconductor fundamentals. In reading the section earlier discussing a P-N junction "depletion" layer, it might have seemed that one should be able to measure the depletion layer potential of a junction using a sensitive voltmeter. This is not the case, however, because as soon as an external circuit of any description, such as a measuring circuit is connected to such a diode, another depletion "layer" forms. It forms in two parts, one at each end of the crystal where the wires connect (see figure 16), and the two "half depletion layer" potentials equal and exactly cancel that of the central junction. With no net circuit voltage, the meter will show nothing.

While we cannot measure the depletion layer voltage of a normal diode, we can measure a voltage across a special type of diode known as a "solar cell." In this type of diode, the "main" P-N junction is made to that it can be exposed to light or heat radiation while the rest of the diode remains unexposed.

Because greater radiation energy is given to the carriers near the exposed junction, the depletion layer which is set up has a greater voltage than that at the connections, which are "dark" and at ambient temperature only. Thus there is a net voltage produced, which can be used to operate small radio receivers or other devices.