

**Electronics**

**Radio**

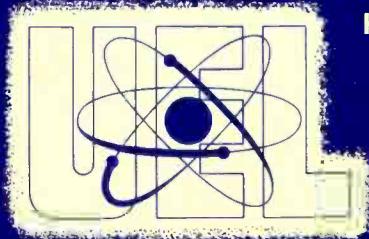
**Television**

**Radar**

**UNITED ELECTRONICS LABORATORIES**

LOUISVILLE

KENTUCKY



REVISED 1967

COPYRIGHT 1956 UNITED ELECTRONICS LABORATORIES

**UNDERSTANDING SEMICONDUCTORS**

**ASSIGNMENT 25**

## Understanding Semiconductors

Some 20 years ago, Dr. William Shockley and his associates, W. H. Brattain and J. Barden, at Bell Telephone Laboratories, were engaged in pure research to classify the electrical characteristics of various types of crystals. As a side-product of this research, they found that a "not quite pure" crystal of a little-known metal, Germanium, could be made to act like a three-element vacuum tube; that is, it detected, oscillated, and even amplified. This "not quite pure" metal, Germanium, is a material that is not quite a conductor, yet it is not an insulator; it is between these two extremes and is called a semiconductor. This discovery led Dr. Shockley and his associates to patent this basic discovery in 1948, and in 1951 Bell Telephone Laboratories announced its new discovery of the transistor—so called because it **transferred** voltage across a **resistor**. This basic discovery led to the development of many devices which operate on various characteristics of these semiconductor materials and have great importance today.

To gain a thorough knowledge of the properties of semiconductors, it will be necessary for us to delve deeper into the nature of matter—to find out just what comprises the various things which make up the universe in which we live. In particular, we will want to know more about the semiconductors and the properties they exhibit which make them operate differently from the conductors and insulators with which we are already familiar.

### The Nature of Matter

There are many different kinds of matter in the universe, and we are all aware of the fact that matter exists in three different forms: solids, liquids, and gases. We know, too, that there are different kinds of matter within these various classifications. Lead, for example, is one kind of matter, while a diamond is another kind of matter. Similarly, in the solids, copper is still another kind of matter and iron is another form of matter. Most of us have seen mercury, which is a liquid, and we have heard of oxygen, hydrogen, and nitrogen, which are gases. These entirely different types of matter are called elements.

There are 103 different known elements in the universe. While there may be more elements than these 103 known types in existence, they have not yet been found, nor has their existence been predicted by mathematicians. A few examples of these 103 elements, in addition to those already mentioned, are uranium, nickel, chlorine, molybdenum, tin, sulphur, potassium, lithium, germanium, silicon, and carbon. Each of these elements is a **different kind of matter**. They can neither be created nor chemically broken down.

An atom is the smallest particle into which matter can be divided and still retain all of the chemical properties of the element.

## The Difference Between Elements, Mixtures, and Compounds

Elements can be combined in two different ways. The result of these two types of combinations are called **mixtures** and **compounds**. When two or more elements are mixed together and do not chemically combine with one another, the result is called a mixture. As an analogy, the mixture of sand, gravel, and cement is used to make concrete. These parts of the concrete do not combine chemically, but are just **mixed** with each other; and each of the three parts of sand, cement, and gravel has no chemical effect upon the other two. Instead, they are merely bound together mechanically.

A compound, on the other hand, results when two or more elements combine chemically. What actually occurs is that the elements actually join together in a form of "holy matrimony" and no longer exist as independent elements, but, instead, represent a new family which is called a compound.

Very often when elements are combined to form compounds, the characteristics of the single atoms are changed as a result of their combination with other atoms. An example of this is common table salt. When sodium, a metal, combines chemically with chlorine, a gas, the compound which we call table salt (sodium chloride) is produced. This compound has entirely different characteristics from either of the atoms which formed it. Another very familiar compound is water, which is made up of two atoms of hydrogen and one atom of oxygen.

When dealing with the basic properties of matter, there is still one other term which should be explained, and this is the term molecule. The molecule is the smallest group of atoms of a compound that retains its chemical identity. Thus, when one atom of oxygen combines with two atoms of hydrogen, this basic combination of the three atoms is called a **molecule** of water.

Now, look at Figure 1, which should illustrate the foregoing. In Figure 1(A) we see in one area a group of oxygen atoms and in another area a group of hydrogen atoms. Figure 1(B) shows the result of combining the two gases, oxygen and hydrogen. Molecules of water are formed, each of which consists of one atom of oxygen and two atoms of hydrogen.

### The Structure of the Atom

As we have learned, the atom is the smallest particle of matter that retains its characteristics as a particular type of element. We have also learned that there are 103 elements, thus there are 103 **different types of atoms**.

Many years ago the British scientist, Ernest Rutherford, and his associates, developed a theory that all atoms are composed of electrically charged particles, and the difference between the various elements results from the

different number of the various electrically-charged particles contained in each atom. Intensive investigation since that time has proved quite conclusively that these atom theories are correct. Each atom is composed of a large central portion, or body, about which lighter particles revolve. The body of the atom (the central portion) is called the **nucleus**. There are two atomic particles which can reside in the nucleus: the **protons**, which have a **positive** electrical charge, and **neutrons**, which have no charge, or, in other words, are electrically **neutral**. The particles orbiting the nucleus are the **electrons**, which, as we have already learned, have the **negative** electrical charge. The proton and neutron are equal in weight and are 1,849 times as heavy as an electron.

Figure 2 shows, in a somewhat simplified form, the manner in which an atom is constructed. Note the protons and the neutrons in the central portion of the atom, and the electrons, which orbit this nucleus. It appears to be very similar to our solar system in which the planets revolve around the sun—on a scale relative to the size of the components, of course. In a stable atom there are as many electrons orbiting the nucleus as there are protons in the nucleus. For example, if there are five protons (positive charges) in the nucleus, there would be five electrons (negative charges) orbiting the nucleus. Looking at the atom from the outside, the negative and positive charges appear to cancel out, and the total charge of the atom is zero.

The electrons orbit the atoms at several different levels, or distances, from the nucleus. There is a definite pattern of the levels at which the electrons orbit the nucleus, and we will consider this matter in detail a little later in this assignment.

## Atomic Weight and Atomic Number

As has been mentioned, practically all of the weight—or mass, to use a more technical term—of an atom is concentrated in the nucleus. Since the protons and the neutrons have equal weight, and are 1,849 times as heavy as the electrons for all practical purposes the weight of the atom can be considered to be the total weight of the protons and neutrons. This total weight of the protons and neutrons in the nucleus is often referred to as the **atomic weight** of atoms. The atoms for each of the 103 elements have different atomic weights.

Another term, which is often used in regard to the atom, is **atomic number**. The atomic number represents the number of **protons in the nucleus**. In a stable atom, the atomic number will also indicate the number of electrons in orbit about the nucleus for, as we have already learned, there are as many electrons in orbit in a stable atom as there are protons in the nucleus. The germanium atom, which will be of particular interest to us, as this is one of the elements used in the manufacture of transistors, has an atomic number of 32. This means it has 32 protons in the nucleus and has 32 orbital electrons.

## The Shells of Atoms

We have seen that the electrons do not orbit the nucleus in a random manner, but, instead, the electrons travel in particular orbits, or shells, as they are often called. There is a maximum of seven shells which can exist around the nucleus, but only a few elements have atoms with this many shells. Some atoms have one shell, some two, some three, and so on, up to the maximum of seven shells.

One of the unique characteristics of the electron shells is that each shell has a **maximum** number of electrons as an upper limit. A shell may contain less than its maximum number of electrons, but it can never contain more than its maximum number. The maximum number of electrons which may be contained in the shell nearest the nucleus is 2, the next shell can never contain more than 8 electrons, the third shell can never contain more than 18 electrons, and the fourth shell can never contain more than 32, etc.

Now let us look at some particular atoms which will illustrate this information.

The element which has the atom with the lightest atomic weight and which is, therefore, the simplest atom in the world is **hydrogen**. The hydrogen atom is pictured in Figure 3(A). Its nucleus has one proton in it, and there is one electron revolving about this nucleus, in the first shell. This first shell (nearest the nucleus) is called the **K** shell.

The **helium** atom is shown in Figure 3(B). There are two protons in the nucleus (this is indicated by the +2 in the center of the drawing), and there are two electrons orbiting this nucleus. Both of these electrons orbit in the **K** shell, as illustrated.

Now let us look at the **lithium** atom as illustrated in Figure 3(C). Notice that the nucleus of this atom has a positive charge of 3 (three protons) and that there are three electrons in orbit about the nucleus. In this case, however, only two of the electrons orbit in the **K** shell, since two is the maximum number that the **K** shell can contain. Thus the third electron must orbit in a shell farther away from the nucleus. This second shell is called the **L** shell. Note that Figure 3(C) illustrates the fact that a shell can have no more electrons in it than the maximum allowable number, and Figure 3(A) has illustrated the fact that it is possible for a shell to have fewer than the maximum number in it, such as the hydrogen atom, which has only one electron in its **K** shell.

The electrons in the second, **L** shell, are no different from the electrons in the first, **K** shell, except that **they have more energy**. Electrons need more energy as the distance to the nucleus increases, because it takes more energy for the electron to orbit in a more distant shell since it has to "reach out" farther in maintaining the attracting force between itself and the nucleus. This can be compared easily to the missile program where it takes more energy to place a missile in orbit 1,000 miles from the earth than it would to place the same missile in orbit only 100 miles from the earth.

When a shell has its maximum permissible number of electrons, as in the case of the **K** shell of helium or lithium, it is said to be "filled." If a shell does not contain its maximum number of electrons, as is the case of the **K** shell of hydrogen and the **L** shell of lithium, then it is said to be "incomplete." In the case of the lithium atom, the **K** shell is thus complete, while the **L** shell is incomplete.

Let us now look at the **chlorine** atom illustrated in Figure 4(A). Chlorine has an atomic number of 17, which means there are 17 negatively charged electrons orbiting a nucleus with 17 positively charged protons in it. This atom has 2 electrons in the **K** shell, 8 in the **L** shell, and 7 in the **M** shell. (In the remaining discussion we will ignore the neutrons in the nucleus, as they merely add to the weight, or mass, of the atom and are not involved in the electrical properties which we will be discussing.)

Figure 4(B) illustrates the **sodium** atom, which has the atomic number of 11 and has 2 electrons in the **K** shell, 8 in the **L** shell, and only 1 in the **M** shell.

Now, we find another rather strange thing regarding the atom. The **K** shell must be completely filled before the **L** shell can ever contain any electrons. Similarly, the **L** shell must be completely filled with its maximum of eight electrons before the next distant shell—the **M** shell—can have any electrons in it. This seems logical, but now we come upon the inconsistency. In the case of the **M**, **N**, and higher shells, it is only necessary for them to have eight electrons in them before other electrons can be present in the more distant shells. This is illustrated in Figure 5.

In Figure 5(A) the potassium atom is diagramed. This atom has an atomic number of 19. It has 2 electrons in the **K** shell, 8 in the **L** shell, only 8 in the **M** shell, and 1 in the **N** shell. Now compare this to the copper atom shown in Figure 5(B). Copper has an atomic number of 29 with 2 electrons in the **K** shell, 8 in the **L** shell, 18 in the **M** shell, and 1 in the **N** shell.

## Free Electrons

Electrons in the **K** and **L** shells are bound very tightly to the nucleus, because of the attraction of the positive charge on the nucleus and the negative charge on the relatively close electron. As a result, these electrons probably never escape from the **K** and **L** shell to become free electrons that may wander from one atom to another.

All **conductors**, such as copper, have one thing in common: their outer shells are incomplete and usually contain only one, two, or three loosely bound electrons. (The outer shells referred to here are those shells farther away from the nucleus than the **L** shell.) When the **M** or **N** shell is nearly full of electrons, the atom is quite stable; but when one of these shells is almost empty (for example, the **N** shell of the copper atom diagramed in Figure 5(B)) then, the electrons in the nearly empty shell are held very loosely. They are free to move from one atom to another adjacent atom if

some outside force attracts them, such as the positive force of an adjacent atom that has lost an electron from its outer shell and thus has a positive charge.

The positively charged atom is called an ion. When an atom loses one or more of its electrons, the total charge of the atom is positive because the protons in the nucleus have a positive charge which is not completely balanced by orbital electrons in the shells. The positive ion thus formed by the absence of an orbital electron has a strong attraction for an electron in the outer shell of a neighboring atom. In this manner, the so-called free electrons can be transferred from one atom to another.

## Chemical Behavior of Atoms

Not only does the number of electrons in the outer shell of an atom determine the conductivity of the material, but it also has a great effect on the manner in which a particular atom acts, chemically. Remember that a stable atom is one in which the outer shell is filled. The helium atom of Figure 3(B) is an example. It contains 2 electrons in its outer shell, which, because of the simple nature of the helium atom, is the **K** shell. Because the **K** shell can never contain more than 2 electrons, it is filled and the atom is stable. Such an atom is chemically inert and will not combine chemically with other atoms. Another chemically inert atom is neon which has 10 electrons: 2 in the **K** shell, and 8 in the **L** shell, which, of course, fills the **L** shell.

All unstable atoms are "hungry." They would like to have enough electrons to fill their outer shell, yet they cannot just acquire any free electrons that might be available because, even though their outer shells are not filled, **the atoms themselves are neutral**. That is, they have just as many electrons in orbit as they have protons in the nucleus. Thus, although they are "hungry," they cannot attract electrons to themselves. What they can do, however, is combine chemically with the atoms of other elements so that they share electrons in their outer orbits. To illustrate this point, look at the chlorine atom of Figure 4(A), which has 7 electrons in its outer shell, and the sodium atom of Figure 4(B), which has 1 electron in its outer shell. When these two are combined into a chemical compound (sodium chloride, or common table salt), the arrangement as illustrated in Figure 6 is produced. Note that the two atoms are **sharing** their outer electrons. Since this is a flat drawing, it still does not completely picture the condition; but if you will envision the 8 electrons present in the combined outer shell of the two atoms as orbiting about the combined nuclei in several directions (more or less as illustrated in Figure 2), you will get the picture. There would be 8 electrons in this outer shell and thus it is complete, although this outer shell actually relates to two different nuclei, rather than just the one as we have considered in connection with single atoms.

As previously mentioned, the electrons present in the outer shell of

atoms determine, to a very great extent, the manner in which atoms react chemically, and the manner in which atoms act as a conductor. As we shall see, this also enters, in a very important manner, into the way in which the transistor operates. The electrons in the outer orbit of an atom are referred to as the **valence** electrons.

## The Periodic Table of the Elements

The differences that exist among many of the elements are known to most people. Iron is known to be different from aluminum and copper; the difference between oxygen and hydrogen is also vaguely known, as are the differences between uranium and lead. It is the many similarities among the elements that are not so well known. In many cases the mechanical or physical properties of some elements are similar, such as copper and aluminum which are soft metals that have a metallic luster and conduct electrical current readily. Similarly, helium and hydrogen are both gases which are lighter than air. Balloons which are inflated with these gases will rise.

Some of the similarities among the elements are due to similar atomic structure of the elements. Often this similarity results from elements having the same number of electrons in the outer orbits (valence electrons), since it is these electrons which determine the characteristics of the elements. Because of the similarities among certain elements of a class, or "family" as they are called, it is possible to arrange the elements into tables according to these properties. The **periodic table** lists the elements according to their atomic properties. Figure 7 shows a periodic table which lists all of the known elements, with atomic numbers from 1 to 103. Examine this table carefully. Note that there are 8 main groups of vertical columns in the table. The elements listed in each vertical column form a family and have the same number of electrons in their outer shells. All elements in Group I of the periodic table have one electron in their outer shells, those in Group II have two electrons, etc., through Group VIII. The family listed under Group **O** contains the elements which have complete outer shells and are, therefore, chemically inert.

The horizontal rows in the periodic table of Figure 7 are called the **periods**. These periods refer to the **number of electron shells**. Thus, hydrogen and helium which are in period 1 have only one electron shell; whereas, the elements in period 3—sodium, magnesium, aluminum, silicon, phosphorous, sulphur, chlorine, and argon—all have 3 shells.

In a similar manner, germanium, arsenic, and selenium appear in period 4 because each has 4 electron shells.

Before leaving the periodic table, let us note one other fact: germanium and silicon are in the same family, or Group. Both are in the grouping of elements with 4 valence electrons.



## Current Flow

Bearing in mind these facts regarding atomic structure, it is possible to understand the subject of current flow.

In previous assignments it was pointed out that electrical current flow is a movement of electrons. The electrons that make up the electrical current are originally all in orbit in the outer shells of the atoms that make up the conductor. These shells are the only source of free electrons in a conductor which can be used to contribute electrons to the flow of electrical current. In any material there is a bond between the electrons and the nucleus, which is the result of the attraction of the negative and positive charges. This bond can be more easily broken in some materials than in others, and it is this factor that determines whether a material is a conductor, an insulator, or a semiconductor.

The bond between the orbital electrons and the nucleus can be broken only by the application of energy. Compare it to a situation wherein a ball is attached to a fixed object by means of an elastic band. If enough force (pull) is applied to the ball, a point will be reached where the elastic band will be broken and the ball will then be freed from the solid object to which it was attached. In the case of an atom, any source of energy can break this bond. Typical sources of energy are heat, light, X-ray, or the electric field resulting from the application of a potential difference.

Every material above the temperature of absolute zero ( $-273^{\circ}\text{C}$ ) is constantly having energy (in the form of heat) supplied to it. In a conductor such as copper or silver, the heat energy of room temperature is sufficient to result in the breaking of the bonds between the valence orbital electrons and the remainder of the atom, thus freeing the electron and producing what is commonly called free electrons. On the other hand, in a good insulator it is virtually impossible to break the electron bonds even by the application of heat, light, X-rays, or an external electric field. Thus, in an insulator, free electrons are not available to produce the phenomena of current flow. In between these two extremes of good conductors and good insulators are the materials which are called semiconductors. (There is another important factor regarding the current flow in the semiconductors used for transistors, and this relates to the crystal lattice structure, which we will consider in detail.)

### Applying Our Knowledge to Semiconductors

Now that we have a good basic understanding of atomic structure, let us apply this knowledge to the semiconductor material, germanium. As the periodic table of Figure 7 indicates, germanium has an atomic number of 32, meaning, of course, that there are 32 orbital electrons. Figure 8(A) illustrates the structure of the germanium atom. There are 2 electrons in the K shell, 8 in the L shell, 18 in the M shell, and 4 in the N shell. Note that there are 4 valence electrons (outer shell electrons), which should be no

surprise to us, as germanium is in Group 4 of the periodic table. Now observe the carbon atom shown in Figure 8(B). This element has an atomic number of 6, with 2 orbital electrons in the K shell and 4 in the L shell. Let us also look at the atom of the silicon element, which, as the periodic table of Figure 7 reveals, has an atomic number of 14 and also contains 4 valence electrons. There are 2 electrons in the K shell, 8 in the L shell, and, as previously mentioned, 4 in the M shell. The structure of the silicon atom is illustrated in Figure 8(C).

Notice in the illustrations of Figures 8(A), (B), and (C) that the valence shells in all three of these elements (germanium, carbon, and silicon) are identical, as each of them has 4 valence electrons. Because the valence electrons determine the characteristics of materials, these elements can be represented by a simplified drawing such as the one shown for germanium and silicon in Figures 9(A) and (B) where we show only the valence shell, or, as it is called, the sub-shell. These drawings are identical, even though the atomic weights of these two elements are different, because both have the same number of valence electrons in their outer shells. Only the valence electrons are shown, together with a charge of +4 on the nucleus to counteract their charge. Remember, it is permissible to use this simplified representation of these elements, because only these valence electrons enter into chemical and electrical action and are free to combine with other atoms to form compounds or contribute to the electrical current flow.

## Crystals

Nature seems to abound in variety. We have already mentioned, for example, that elements can exist in the form of gases, liquids, or solids. Similarly, we know that various elements are different colors and have a lot of other different properties. One property which some materials possess is a crystalline structure. Most of us have, from time to time, seen a quartz crystal or perhaps a sugar crystal which developed in Grandma's jelly when she didn't make it quite right. Some materials take on the crystalline structure naturally, such as quartz. Some can never be in crystalline structure; for example, gases. Others can be in crystalline structure under certain conditions and not in crystalline structure under still other conditions. One material which is sometimes in crystalline form and sometimes not in crystalline form is carbon. It so happens that, in most instances, carbon takes the noncrystalline form. Most of us are familiar with the dull, black appearance of noncrystalline carbon. However, if this noncrystalline carbon is subjected to extreme high pressures and extreme high heat, it can be forced into a crystalline form. Then, strange as it might seem, this crystalline form of carbon bears no resemblance to the noncrystalline form. The crystalline form of carbon is diamond! In spite of the fact that ordinary carbon and diamond look entirely different and have other properties which are entirely different (diamond is extremely hard; ordinary carbon is soft, etc.), both are formed from the same carbon atoms as pictured in Figure 8(B), or which

could be represented by a simplified drawing as shown in Figure 9. What causes the difference in the properties, then? This difference results from the **lattice** construction of the diamond crystal.

The lattice construction of the diamond crystal is shown in Figure 10. The spheres in this diagram represent the atoms of carbon, and the rods running between the spheres represent the electron pairs which hold the spheres together. We will consider these electron pairs in greater detail in a moment. Note that the arrangement is not just a helter-skelter arrangement, as the atoms in ordinary carbon. Instead, the atoms take on a definite arrangement in the lattice structure of a diamond, and they are bound together very tightly in this structure. To appreciate the strength of this binding (called covalent bonding), consider the extreme hardness of a diamond.

The semiconductor materials used in transistors have atoms which are arranged in a lattice structure very similar to that of the diamond crystal illustrated in Figure 10. An expanded view of the lattice structure of a germanium crystal is shown in Figure 11. In this figure, the interconnecting bar, or rod, between the atoms represents the covalent bond. (Photographs have recently been taken of crystal lattice structures using a newly developed technique. These photographs show the nuclei of atoms, bound together with interconnecting fields of force—similar to the bar shown in Figure 11—giving visual proof that this theory regarding the lattice construction of crystals is correct.)

## Covalent Bonding

To understand just how the covalent bonding occurs in the germanium crystal, let us consider Figures 12(A) and 12(B). You will recall that germanium has 4 electrons in its outer shell [see Figure 8(A)] and that it can be represented as shown in Figure 9(A). We have also learned that atoms become stable when their valence shell is filled with 8 electrons. Crystalline germanium is a stable atom and thus it might seem that two atoms would combine, much as the sodium and chlorine atoms combine in the Figure 6 illustration, so that the 4 valence electrons from one germanium atom would combine with the 4 valence electrons from another germanium atom to form an 8 electron shell. This **would** produce a stable germanium atom, but nature will not permit such a combination. The exact reason why this type of combination cannot occur involves a rather complex chemical explanation; but, in general, the combination cannot occur in this manner because we are talking about two **similar** atoms. In chemical compounds, such as the sodium chloride we have already discussed, the combination occurs between two **dissimilar** atoms. The fact that they operate exactly opposite to one another, chemically, makes the combination possible. In germanium, however, we're talking about two similar atoms, thus they cannot combine directly with the 4 outer electrons of one sharing an orbit with the 4 outer electrons of another. Therefore, a somewhat modified version of

this procedure must take place to produce the covalent bonding which has been explained.

Nature will permit a germanium atom to share **one** valence electron with **one** of its neighboring germanium atoms. [See illustration in Figure 12(A).] This is only the first step of the story, though, and Figure 12(B) illustrates the complete arrangement. Note the atom shown in the center of the drawing. This atom is sharing covalent electrons with the atom to its right, just as illustrated in Figure 12(A). Similarly, it is sharing covalent electrons with the atoms shown directly beneath it, other covalent electrons with the atoms shown to the left of it, and its fourth electron is being shared with the atom shown above it. Thus, each of its valence electrons enters into a covalent relationship with a separate neighboring atom.

If Figure 12(B) is compared with Figure 11, it can be seen that these are two representations of the same thing. Notice in Figure 11 that the atom shown in the center is connected to its neighbors by means of shared pairs of electrons. Of course, this represents only a minute part of the overall structure, and each one of the atoms on the ends of the rods in Figure 11 would be sharing its valence electrons with its neighbors, etc.

As has been mentioned, the combining of atoms in this manner is called **covalent bonding**; the **valent** portion of the word **covalent** having to do with the valence electrons, and **co-**, of course, meaning between **two**. As may be noted in the atom shown in the center of Figure 12(B), **the valence shells of the atoms so bonded** contain 8 electrons. These shells are, therefore, **complete**. Thus, the semiconductor is a very stable material. Since the drawing of Figure 11 is rather difficult to represent, the crystal lattice is usually depicted in a two-dimensional drawing similar to that of Figure 13. Note that this shows exactly the same condition as that shown in Figure 12(B) or in Figure 11.

If a germanium lattice were placed in an electrical circuit, some current would flow but it would be small compared with the amount of current that would flow through a conductor with the same voltage applied. The current flow would be held to a very low value because of the strong covalent bond, as we have indicated in the foregoing discussion. Because of this strong bond, even with the applied voltage, it is difficult to knock the electrons out of their places in the crystal lattice structure: the valence shells are complete and the atom is very stable. (The fact that a few electrons can be knocked out of the lattice structure so that some current does flow makes it possible to classify the material as a semiconductor, rather than a conductor.)

Referring to Figures 8(A) and 8(C) and the simplified representation of germanium and silicon in Figures 9(A) and 9(B), it will be recalled that both of these elements have 4 valence electrons, and, as the valence electrons determine to a very great extent the characteristics of the materials, it would seem reasonable to assume that these two materials would operate in a similar fashion. Such is the case. The covalence bonding properties of silicon closely parallel the covalent bonding of germanium. Thus, the lattice arrangement

illustrated in Figure 13 for germanium applies equally well to silicon. Both of these materials are used widely in transistors and other solid-state devices.

## Energy Diagrams

It was pointed out that in some materials (good conductors) such as copper, the heat energy of room temperature is sufficient to free some valence electrons. The conductive properties of materials can be presented by means of simple drawings called **energy diagrams**. Figure 14(A) is an energy diagram which represents the condition we have just explained for a conductor. When the electrons are in the valence shell of the atom, which is represented by the **valence band** in the energy diagram, they are not available for current flow. However, the heat energy supplied to the conductor (simply because the conductor is above absolute zero in temperature) moves some of these electrons from the valence shell so that they become free electrons, and are available for conduction. This is represented by the conduction band of Figure 14(A).

Now let us examine the energy diagram for an insulator, as illustrated in Figure 14(B). Notice in this diagram that there is a region called the **forbidden region** which separates the valence band and the conduction band. Only the application of a very high amount of energy to an insulator will make it possible for the valence electrons to jump across the forbidden region and thereby enter the conduction band. The energy diagram, therefore, shows that it is difficult for the valence shell electron to be freed and thereby become current carriers.

Perhaps reference to an example cited earlier in this assignment will explain the forbidden region a little more clearly. It was mentioned earlier that the valence electrons might be compared to a ball attached to a fixed object by means of an elastic band. In an insulator, these valence electrons are tightly bound to the atom, and if external energy is applied in the form of heat, electrostatic field, X-ray, or any other means, these electrons will be affected to a certain degree. However, they will not be released from the valence shell until the amount of energy supplied is enough to overcome the force holding them in the atom. Thus, in our example, this would be equivalent to having to apply enough force to break the elastic band holding the ball to the solid object. If any less energy is applied, the elastic band would not be broken and the ball would fly back toward the wall. Similarly, as indicated by the energy diagram of Figure 14(B), the valence electrons cannot move from the valence band into the conduction band unless enough energy is provided to completely overcome the amount of energy represented by the forbidden region. This forbidden region is also often referred to as being an **energy gap**.

In an insulator, this energy gap, or forbidden region, between the valence band and the conduction band is so wide that electrons almost never cross from the valence band to the conduction band. The better the insulator, the

wider this gap, and the rarer it becomes for an electron to cross over into the conduction band. In a good insulator a very great amount of energy would be required to break the "elastic band" holding the valence electrons to the nucleus. This large amount of energy can be supplied by only such things as extremely high voltages, etc. This is why an insulator cannot conduct current under normal conditions.

Because a conductor has no forbidden region and an insulator has a wide forbidden region, it would seem logical that a semiconductor would have a narrow forbidden region. This is true for pure semiconductor materials. The comparison of the energy bands for conductors, semiconductors, and insulators is given in Figure 14(C).

## **Intrinsic and Extrinsic Semiconductor Material**

Semiconductor material which is **pure** is called **intrinsic** semiconductor material. Thus, pure germanium is intrinsic semiconductor material, as is pure silicon. Although the energy diagram for intrinsic germanium or silicon would normally be illustrated as shown in Figure 14(C), it should be pointed out that the width of its forbidden region will vary with temperature. Near absolute zero (minus  $273^{\circ}\text{C}$ ), a pure semiconductor acts much as an insulator, because the valence electrons are held rigidly in their role of forming covalent bonds. At room temperature, however, intrinsic semiconductor materials do have some conductivity as a result of valence electrons being freed from their covalent bonds by thermal energy (heat energy), which gives them sufficient energy to break loose from the bond and jump across the forbidden region into the conduction band.

If sufficient energy (energy from heat, electric field, X-ray, etc.) is applied to a germanium crystal, there will be more conduction as more electrons jump over the forbidden region to the conduction band. Under the best of energy conditions, however, very little current flow will take place in a pure semiconductor material such as germanium, because of the strong bond produced by the covalent bond in the crystal lattice structure of the material. As a result, something must be done to intrinsic semiconductor material to increase its conductivity before it can be put to practical use in semiconductor devices. To accomplish this result, impurities are added to intrinsic semiconductor material, producing what is often referred to as **extrinsic** semiconductor material.

## **Semiconductors and Impurities**

When semiconductor materials are prepared for use, the first step in the process is that of purifying the material: germanium or silicon. This process is continued until an extremely pure semiconductor material is obtained. After this, controlled amounts of certain impurities are added to produce extrinsic semiconductor material.

The amount of impurities added to intrinsic semiconductor material must be carefully controlled because, if too much impurity is added, the semiconductor material will lose the conduction characteristic of a semiconductor and become a conductor. Under such a condition, it would be worthless for use in transistors.

The process of purifying the semiconductor material is sufficient to remove almost all of the impurities that might exist in the raw semiconductor material, so that there is no more than perhaps one impurity atom per billion semiconductor atoms of the material. To convert this into suitable extrinsic semiconductor material for transistors, occasional atoms (.05 to 8 impurity atoms to 1 million semiconductor atoms) are placed in the semiconductor material while it is in a molten state. They enter into the crystal lattice structure of the material. This addition of impurities to the semiconductor material is called **doping** and produces semiconductor material that has either a **deficiency, or surplus**, of valence electrons that are required by the covalent bonds. Whether there is a deficiency or surplus of valence electrons depends upon the type of impurity added, as we shall see in the following discussion. In either case, however, the conductivity of the material is increased by the addition of the impurity atoms.

## **N-type Semiconductor Material**

Refer to the periodic table of Figure 7 and note that germanium is in Group IV which, as we have learned, tells us each atom has four valence electrons. The covalent bonding properties of the germanium, then, produces a crystalline structure with a lattice work arrangement as illustrated in Figure 13.

Let us now see what will occur when an impurity atom with five valence electrons is added to pure germanium while it is in a molten state. For example, let us add a few impurity atoms of arsenic which, as the Periodic Table reveals, has five valence electrons in each atom. These impurity atoms will diffuse throughout the entire crystal lattice and will take the place of some of the germanium atoms in the lattice construction. These will produce the lattice arrangement illustrated in Figure 15. Notice that the arsenic atom shown in the center of the diagram has entered into a covalent bonding arrangement with its four neighbors; but, **as the atom of arsenic has five valence electrons, there is one electron left free**. It is bound **very** loosely to its original arsenic atom and can be easily attracted by any positive charge which may be near it. In other words, there is one free electron introduced into the lattice structure for each atom of the arsenic impurity which has been added. Since the impure, extrinsic semiconductor now has excess electrons, it is called N-type material, because these excess electrons, of course, have **negative** charges.

Impurity atoms that produce N-type semiconductor material by providing excess electrons for conduction are called "donor" atoms because they **donate**

free electrons to the crystal lattice. Donor atoms are therefore those atoms having five valence electrons which, when added to an intrinsic semiconductor material having four valence electrons, leave one free electron for each impurity atom added to the material.

Let us look at this same phenomenon, referring to the energy diagram as illustrated in Figure 16. Forgetting the portion of this diagram labeled "excess electrons" for the moment, note that this energy diagram is similar to those which have been presented previously for semiconductor material. In other words, when the excess electrons are temporarily ignored, we will have the energy diagram for most of the semiconductor material in the crystal lattice. However, the donor material added to the lattice has put free electrons into the lattice structure, and these are illustrated in the energy diagram of Figure 16, labeled "excess electrons." These electrons are held quite loosely and are therefore quite close to the conduction band. They will therefore require only a small amount of additional energy to "jump" to the conduction band. When these electrons are moved into the conduction band by some external source of energy, they become free electrons that can contribute to current flow.

The electrons (which have been provided by the donor impurities) shown in the "forbidden region" are at a level called the donor level. Electrons from this level are "donated" to the conduction band. Since only a small number of impurity atoms are added to the intrinsic semiconductor material, only a relatively few of these "excess" electrons are present; most of the atoms of the extrinsic N-type semiconductor material will be those of the Group IV crystal of the Periodic Table.

## **P-type Semiconductor Material**

Now let us see what will occur if an impurity atom from Group III of the Periodic Table is added to the semiconductor material of Group IV. For example, let us say that a controlled number of indium atoms are added to intrinsic germanium while it is in a molten state. These atoms will enter into the lattice construction of the germanium, as illustrated in Figure 17. However, as the atoms in Group III of the Periodic Table have only three electrons in their valence shells, we will now have a different condition from that which occurred when a Group V impurity was added to the germanium. Since the indium atom shown at the center of Figure 17 has only three valence electrons, it cannot enter into the covalent bonding as completely as another germanium atom could. Obviously, there is one electron missing in the shell formed by the covalent bonding with one of its neighbors, since there are only seven electrons present and eight are required for a complete shell. Thus, there is a **deficiency** of one electron, and this deficiency is referred to as a **hole**.

When extrinsic semiconductor material has a deficiency of electrons it is called P-type material, because this deficiency of one electron in the covalent crystal structure produces a positive charge.



Figure 17 shows just one hole associated with the one indium atom, illustrated in the lattice structure. However, there are, of course, billions of germanium atoms and hundreds of thousands of indium atoms in a typical piece of P-type germanium. Thus, there are many of these holes present.

From what we have learned in the past regarding conduction, it would seem that these holes (which, of course, represent a deficiency of electrons) would leave the material in a poor state of conduction. However, in P-type semiconductor material this is **not** the case, because the main conduction current in this material **does not** use electrons. (Think about this statement and we'll discuss it shortly.)

## The Energy Diagram for P-type Semiconductor Material

Figure 18 shows the energy diagram for P-type semiconductor material. Once again, if we ignore the portion of this diagram labeled "deficiency of electrons," we will see that it represents the energy diagram for intrinsic semiconductor material which we have considered previously. Now note that in this diagram at the level labeled "acceptor level" there is shown a region representing the deficiency of electrons or, in other words, **holes**. As we have mentioned, these holes have a **positive charge**. They possess an energy level which is quite close to the valence band. As a result, with the application of a small amount of external energy, electrons from the **valence** band can be attracted by these holes.

In P-type material, when a little energy is added to an electron in the valence band, the electron will have sufficient energy to occupy the hole energy level. When this happens, the hole is said to be "filled." In the original location of the electron which moved to occupy the hole, another hole has been created. As a result, every time an electron from the valence band moves forward to fill a hole, the hole appears to move in the reverse direction. Perhaps a familiar illustration will make this point clear.

Filling a hole in the valence band of a P-type semiconductor material can be compared, as an example, to a man who enters a theater, walks down an aisle and expects to find an aisle seat. However, the only empty seat (literally, a "hole") is at the far end of the row. Rather than walk around to the unoccupied seat, he asks the spectators to "move" the empty seat (hole) toward him, so that he can be seated. Obliging, the person seated next to the empty seat (hole) moves into the empty space (thus occupying the "hole"), leaving his former seat unoccupied. His former neighbor, in turn, moves into the seat just vacated. This, again, leaves an empty seat. This process continues until the "hole" has moved across the row. The man can then sit down and occupy the "hole," which has effectively moved across the theatre to him.

It is easy to see that, literally, the "hole" (empty seat) has moved from the far end of the row to the near aisle, as the occupants moved—one seat

at a time—from the near aisle to the far aisle. If we make the people in the seats represent electrons, and the empty seat represent the hole in the valence bond of a semiconductor material, then we'll note that the movement of holes is in the opposite direction to the movement of electrons. It is by this movement of holes—positive charges—that semiconductor theory differs from vacuum tube theory. Bear in mind that although a hole represents a "missing electron," it is far more than just a condition where something is missing. It actually has a positive charge, and, under the influence of an external source of energy such as the electric field supplied by a potential difference, these positive charges will move. In other words, the **holes may be considered to be mobile positive charges**, just as electrons can be considered to be mobile negative charges.

## Acceptor Atoms

The impurity atoms (atoms with three valence electrons) which are added to intrinsic semiconductor material to produce P-type semiconductor material are called **acceptor atoms**. (The holes in the "forbidden region" **accept** electrons from the valence band of the semiconductor material.) Therefore, any impurity atom from Group III of the Periodic Table is an **acceptor** impurity because its three valence electrons, combined with the four valence electrons of the Group IV semiconductor material, leave a deficiency of one electron in the covalent bond at a certain energy level (called the **acceptor level**, because electrons are accepted at this level from the valence band).

## Majority and Minority Carriers

Even though semiconductor material is refined as much as possible before it is "doped" to form either P-type or N-type material, a certain amount of impurities will still be present. For this reason, when N-type material is produced, there will be some impurities present which may have a deficiency of valence electrons and thereby produce a few covalence bonds with holes. Similarly, in P-type material, some impurity atoms will be present with more than four valence electrons, which will thereby produce some covalence bonds with excess electrons. These impurities will, therefore, tend to produce a small amount of conduction, which is of a nature opposite to that of most of the conduction within the semiconductor material. The appropriate charge carriers (electrons in N-type material and holes in P-type material) are called the **majority** carriers, while the unwanted impurity carriers are referred to as the **minority** carriers.

## Recombination of Holes and Electrons

A question might arise as to why the holes and electrons do not recombine: "If a hole is actually the absence of an electron, why don't they all combine, each then removing one hole and one electron pair from the carriers

moving in the crystal lattice of the semiconductor material?" This actually does take place in a semiconductor which contains both majority and minority carriers. The rate of recombination of the holes and electrons is determined primarily by the number of minority carriers. Thus, it is apparent that, unless minority carriers are kept to a minimum, the desired properties of the semiconductor materials would be canceled out by the undesirable characteristics produced by the impurities.

There is another factor which should be explained at this point, although it has been mentioned previously. The covalent bonds can be broken by the application of external energy such as heat, light, X-rays, etc. When the covalent bond is broken, an electron-hole pair will be formed. The thermal energy which is produced at room temperature causes a certain number of these electron-hole pairs to be formed in a semiconductor material, and this is what actually establishes the conductivity of intrinsic semiconductors. These electron-hole pairs will be neutralized by the absorption of an electron by the hole, and by the movement of the electron into another hole.

## **Current Flow in Semiconductor Materials**

To briefly summarize the manner in which current flow takes place in semiconductor materials, refer to Figures 19(A) and (B). Figure 19(A) shows a piece of N-type semiconductor material connected in a circuit containing a battery. Since this is N-type material, there will be some free electrons available, as a result of the excess electrons from the covalent bonding of the impurity atoms; so, current flow within the semiconductor will take place from the negative terminal to the positive terminal, as indicated. Note that the current flow within the N-type semiconductor material is much the same as current flow within a conductor, in that there is a gradual movement of electrons from the negative source of potential, toward the positive source. Since this is a semiconductor material rather than a conductor, this flow of current will be relatively small.

Now, notice the situation regarding P-type semiconductor material as illustrated in Figure 19(B). Once again the battery is connected as in the previous drawing, and the current flow in the external circuit from the battery to the semiconductor material itself is in the same direction as previously. However, the current flow within the semiconductor itself is of an entirely different nature. The P-type semiconductor material contains holes (mobile positive charges). When the battery is connected as shown, the holes near the negative connection will be attracted by the negative charge and will move toward this terminal, and at the same time the holes near the positive terminal will be repelled and move away from the positive terminal.

The situation is the same as if the holes moved within the semiconductor material, from the positive terminal to the negative terminal, as illustrated. In actuality, the situation is a little more complex than illustrated, for, as the positively charged holes move toward the negative terminal, electrons from

the negative terminal move toward the holes and the two charges are neutralized. Similarly, throughout the entire length of the P-type semiconductor material the movement of the holes from the positive terminal toward the negative terminal is such that a hole never moves the entire length of the material. Instead, the hole moves a little and is neutralized by an electron which it attracts from another atom. What is actually taking place is that the holes are moving from the positive to the negative terminal, whereas electrons are moving in the direction from the negative terminal to the positive. For practical purposes, however, it is most convenient to consider merely the movement of holes from positive toward negative. Note, however, that in the external circuit the current flow is identical to that with which we are familiar. The current flow is from the negative terminal of the battery toward the semiconductor, and from the opposite end of the semiconductor toward the positive terminal of the battery.

## **P-N Junctions**

We have learned that in N-type semiconductor material the main current conduction is by means of electron flow which moves from negative to positive in the conventional manner of electrons flowing through a conductor. In a P-type semiconductor, however, the main source of current flow is by reason of holes in the material which have the effect of flowing or moving in the opposite direction from conventional electron flow, so that they move from positive to negative. This shows that we have produced two materials having essentially opposite charge characteristics. Individually, neither of these is particularly useful for practical applications. When we join the two materials together, however, certain things happen at the junction of the two materials which make it possible to control the current flow through the two materials and thereby control the amount and direction of current flowing to the junction formed by the two adjoining materials.

The simplest semiconductor device that can be formed using P-type and N-type semiconductor materials is the simple junction device in which a piece of P-type material is joined to a piece of N-type material. To understand what occurs examine Figure 20.

In Figure 20(A) we see two blocks of semiconductor material: the P-type which contains holes, and the N-type which contains free electrons. Let us review a few facts regarding these two blocks of semiconductor material before proceeding. The P-type material has holes in it; in other words, it contains impurity atoms which have only three valence electrons. When these atoms form covalent bonds with the germanium atoms, the outer shells are not complete and this produces the condition which we refer to as holes. Let us emphasize that, although these atoms contain holes which are in themselves "hungry," the atoms themselves are neutral. In opposition, the N-type material contains impurity atoms having five valence electrons which, when combined with germanium atoms, complete the covalence bonding but leave

one electron very loosely held. As long as this electron is held within the lattice structure, however, the atoms are neutral.

Now, let us see what occurs when the P-type and N-type semiconductor materials are bonded together, as shown in Figure 20(B). On the N side of this junction there will be free electrons, while on the P side of the junction there will be holes. Obviously, these two unlike charges will attract one another. The electrons in the N-type material will move toward the junction to combine with the holes, while the holes in the P-type material will "move" toward the junction to join with the electrons. It might seem that all of the free electrons from the N material would combine with an equal number of holes from the P-type material, but this is not the case. Remember that before the two pieces of material were joined, the individual atoms in each were in a neutral state of charge. Now let us assume that one of the free electrons from the N-type material fills a hole in the P-type material near the junction. This means that the donor material on the N side of the junction has lost an electron, leaving this atom with a positive charge. Likewise, on the P side of the junction the acceptor impurity atom, whose hole has been filled, has gained an electron so that it now has a negative charge. This process of negatively charged acceptor atoms, and positively charged donor atoms being produced continues all up and down in the region where the two types of material join, as illustrated in Figure 20(C). This process uses up the holes and the free electrons in the region of the junction, forming what is often referred to as a **depletion region**. Thus, the holes in the P-type material are separated from the free electrons in the N-type material by this depletion region. As a result, a state of equilibrium is produced wherein the majority of the free electrons in the N-type material cannot move freely past the barrier represented by the depletion region into the P region to neutralize the holes located there. The depletion region is often referred to as the **barrier region**.

Note in Figure 20(D) that there are oppositely charged particles on the two sides of the junction. From the theory we have learned previously in the training program, we can see that this resembles two different things we have already studied: (1) it resembles a capacitor, and (2) it resembles a battery. As a matter of fact, this region does actually exhibit the properties of both of these components. There is an actual capacity effect present, which in most junction diodes will be on the order of only a few micro-micro farads (picofarads). The depletion region also looks like a small battery. The potential difference across the junction will average approximately .3 volt for germanium material and .6 volt for silicon material. Figure 20(E) illustrates these two characteristics of the junction.

## **The Energy Diagram for the P-N Junction**

Let us look at this same situation using the energy diagram illustrated in Figure 21. Notice that the left portion of this diagram is similar to the energy diagram in Figure 18 for P-type semiconductor material, while the

right portion of the diagram is equivalent to the energy diagram we have already studied for N-type material, as illustrated in Figure 16. Recall, also, that the excess electrons in the N material and the deficiency of electrons, or holes, in the P-type material make possible current flow in these materials. It is also these two things (the excess electrons and the holes) which produce the current flow in a P-N junction. Thus, the two energy diagrams are arranged with these two levels—the donor level and the acceptor level—“lined up.” This diagram shows that to travel from the N-type material to the P-type material the free electrons must climb an energy “hill.” This shows, graphically, the same thing we stated previously—that the depletion region represents a barrier to the movement of the electrons from the N material to the P material.

The same situation is true regarding the holes, as illustrated in Figure 21. At first glance it would appear that the diagram indicates that the holes would move easily down the energy hill. The reason this is not true, however, is the fact that the holes represent the opposite charge to that of the free electron, and it is therefore just as difficult for the holes to move down the hill as it is for the free electrons to move up the hill.

The barrier region is like a brick wall which keeps the electrons and holes from passing unless they have sufficient energy to rise over the barrier, just as it is possible for a running start to give one sufficient energy to jump over a brick wall. This energy can be supplied by any external source of energy, but is usually supplied by means of an external difference of potential (battery).

## The Biased P-N Junction

When an external voltage is connected to a P-N junction, the junction is said to be **biased**. Since there are two ways a battery can be connected to a P-N junction, there are two ways the junction can be biased: **reverse** biased and **forward** biased. (See Figure 22.)

### Reverse Bias

When the P-N junction is reverse biased, the external battery is connected so that the negative terminal of the battery connects to the P material and the positive terminal of the battery connects to the N material, as illustrated in Figure 22(A). Now let us see what happens within the semiconductor. As illustrated, in Figure 23(A), the holes in the P material move toward the negative terminal, because the positive charges of the holes are attracted by the negative applied voltage. At the same time, the free electrons in the N material will be attracted toward the positive terminal of the battery and will move as illustrated in Figure 23(A). Note that the holes move away from the junction at the same time the electrons move away from the junction. This action will occur only an instant and then there

will be no current flow, for there is no way for conduction carriers (holes and electrons) to cross the barrier to complete the conduction path.

Notice here that the negative terminal of the battery attracts the holes away from the junction, while the positive terminal of the battery attracts the electrons away from the junction. With both the holes and the electrons acting **against** the flow of current through the junction, a very high resistance path is set up. In other words, the reverse bias arrangement makes it even more difficult for current to flow through the junction than that presented by the depletion region. The effect of reverse bias, then, is to raise the "brick wall" even higher, making it that much more improbable for conduction to take place.

It should be mentioned, however, that there is a small amount of conduction current across the junction, even with the reverse bias. This is a "leakage" current resulting from the flow of minority carriers and the slight amount of current produced from energy supplied to the crystal in the form of light, heat energy, etc.

## Forward Bias

Let us see what happens when the battery connections to the N and P materials of the junction are connected as shown in Figure 22(B), forming the forward bias arrangement. With forward bias, the P side of the junction is connected to the positive terminal of the battery, and the N side of the junction is connected to the negative terminal of the battery. As Figure 23(B) shows, the negatively charged electrons in the N material will now be repelled toward the junction as a result of the negative charge of the battery terminal. Similarly, the positively charged holes will be repelled from the positive battery terminal, toward the junction. We've already explained how the holes move (remember the analogy of the theater seats), and in this manner the holes move toward the junction. At the same time the free electrons move toward the junction on the N side. If the applied battery voltage is greater than the voltage built up by the depletion region, the electrons and the holes will be given sufficient energy to "jump the barrier," or, in other words, to jump the "brick wall." Thus we see that **forward bias will permit current flow**, whereas **reverse bias will prevent current flow**.

Also note, in Figure 23(B), the current flow in the external circuit. Note that electrons from the negative terminal of the battery enter the N material to replace each free electron contributing to current flow, in a manner quite similar to that which takes place in a conductor. Similarly, every time a hole moves away from the "end" of the P-type material, an electron is freed, enters the conductor, and flows to the positive terminal of the battery. Therefore, the holes do not actually enter into the current flow in the external circuit; their action is limited to the semiconductor itself. As a result of an electron being supplied from the battery to the N material each time an electron leaves the P material (both of these actions occurring

each time an electron and hole recombine near the junction), the semiconductor material does not “run out of” either free electrons or holes.

## Summary of Biasing

Figure 23 illustrates that when a P-N junction is reverse biased, it will not conduct; when it is forward biased, it will conduct. This is similar to the action of a type of vacuum tube which was studied in an earlier assignment. We have learned that when an external voltage makes the plate of a diode positive with respect to the cathode, the tube will conduct; when the plate is made negative with respect to the cathode, the tube will not conduct. In this way, the P-N junction functions like a diode, and this is exactly what it is. The P-N junction is a diode and is often called a **junction diode**.

A junction diode is biased in the forward direction when the P material is made positive (connected to the positive source of potential) and the N material is made negative (connected to the negative terminal). Reverse bias, which prevents conduction across the junction, exists when the P material is made negative and the N material positive.

## Schematic Symbol

There are two schematic symbols which are used to represent junction diodes, as shown in Figures 24(A) and (B). The one shown in Figure 24(B) is more widely used. An explanation of this symbol is shown in Figure 24(C). Notice that the arrowhead represents the P-type material and the straight line of the symbol represents the N-type material.

There is a simple method which can be used to remember how a junction diode is **forward biased**: the P-type material must be positive. If the symbol employing the arrowhead and heavy straight line is used, the arrowhead which points must be positive.

When compared with vacuum tube operation, the P-type material is equivalent to the plate, or anode, and the N-type material is equivalent to the cathode. These designations—anode and cathode—are often used in relation to semiconductor diodes.

Figure 25 illustrates the two possible biasing arrangements for semiconductor diodes, using the schematic symbols. Figures 25(A) and (B) illustrate reverse bias, and Figures 25(C) and (D) illustrate forward bias.

## Uses of Junction Diodes

As we delve into complete circuits for electronics equipment, we will find more and more uses for junction diodes. Three typical uses are illustrated in Figure 26. Let us analyze these, briefly. Figure 26(A) shows a junction diode used as a rectifier in a power supply. Remember that the diode will conduct when its anode is positive with respect to its cathode, and



it will block current flow when the reverse polarity is applied to it. The input to the rectifier is an a-c signal so that on one alternation the anode is made positive; whereas, on the other alternation, it is made negative. When the anode is positive the diode will conduct, and when the anode is made negative it will not conduct. Consequently, a pulsating d-c current flows through resistor R and produces the pulsating output voltage illustrated in the figure. When the filter shown is added, an almost pure d-c output is obtained.

In Figure 26(B) we see a junction diode used as the detector in a radio receiver. Detection action will be explained in detail a little later in the training program, but essentially it is also a matter of rectification and the junction diode serves to provide this action in the circuit illustrated.

Figure 26(C) illustrates an interesting application of a junction diode arranged in one form of a circuit often called a clipper circuit. Let us assume that in some industrial electronics application there is a series of pulses, as labeled "input signal" in Figure 26(D). Some of these pulses are of very low value; others are in the order of several volts. Let us assume that in our particular application, for some reason, it is desired that only those pulses which exceed a 3-volt level should be used. Notice in the circuit that a 3-volt battery is connected so that the diode is reverse biased, with the anode connected to the negative end of the battery, and the positive end of the battery connected to the cathode through resistors. Under such conditions there will be no output when the input signals are less than 3 volts in amplitude.

Note, however, the condition which occurs when the second pulse shown in the input signal (exceeding 3 volts) is applied. This voltage is greater than the 3 volts of the battery and overcomes the reverse bias, applying approximately one volt of forward "bias" to the junction diode. Under these conditions the junction will conduct, and the output signal as shown at two in Figure 26(E) will be developed across resistor R. Since pulse 3 has an amplitude of less than 3 volts, it will not overcome the reverse bias, so no current flow will take place. However, pulses 4, 5, and 6 have amplitudes greater than 3 volts and would therefore produce output pulses as shown.

These circuits are shown here merely to provide some indication of the actual use of junction diodes. As we shall learn, there are many, many uses for diodes. However, of greater importance than diodes themselves are the other developments which have occurred in the semiconductor field: transistors and other 3- and 4-element semiconductor devices. Since the discovery of the amplifying properties of semiconductor materials, the best brains and resources of many laboratories and industrial firms have been devoted to developing these characteristics into practical devices. The electronic devices resulting from the discovery and development of the useful properties of semiconductors constitute not just a development, but a virtual revolution. Just as the electric bulb not only supplanted the kerosene lamp but also opened new and unexpected fields of usefulness for electricity, so, too, semiconductor devices are revolutionizing electronics.

The next step in our complete understanding of semiconductor devices will be to consider transistors in detail in a forthcoming assignment.

## Test Questions

Use a multiple-choice answer sheet for your answers to this assignment.

The questions on this test are of the multiple-choice type. In each case four answers will be given, one of which is the correct answer, except in cases where two answers are required, as indicated. To indicate your choice of the correct answer, **mark out** the letter opposite the question number on the answer sheet which corresponds to the correct answer. For example, if you feel that answer (A) is correct for question No. 1, indicate your preference on the answer sheet as follows:

1. ~~(A)~~ (B) (C) (D)

**Submit your answers to this assignment immediately after you finish them. This will give you the greatest possible benefit from our personal grading service.**

1. (Check two)

- (A) The central portion of an atom is called the electron.
- ~~(B)~~ The central portion of an atom is called the nucleus.
- ~~(C)~~ The proton has a positive charge.
- (D) The neutron has a positive charge.

2. How many known elements, or kinds of atoms, are there?

- (A) 32.
- (B) 77.
- ~~(C)~~ 103.
- (D) 144.

*106 elements known as of now do!*  
*Real elements = 118*

3. The weight, or mass, of an atom can be considered to be the weight of:


- (A) the electrons.
- (B) the protons.
- ~~(C)~~ the neutrons plus the electrons.
- ~~(D)~~ the protons plus the neutrons.

4. The atomic number of an atom is equal to: (Check two)

- ~~(A)~~ the number of protons in the nucleus.
- (B) the number of neutrons in the nucleus.
- (C) the number of protons plus the number of neutrons.
- ~~(D)~~ the number of electrons in orbit about the nucleus.

5. The maximum number of electrons that can be located in the **K** shell of an atom is:

- ~~(A)~~ 2.
- (B) 8.
- (C) 18.
- (D) 32.

6. The covalent bonding produced by the addition of an impurity atom with three valence electrons to intrinsic germanium will have (neglect minority carriers) :
- (A) free electrons.
  - (B) "holes."
  - (C) neither free electrons nor holes.
  - (D) both free electrons and holes.
7. (Check two)
- (A) In N-type semiconductor material the majority current carrier is free electrons and the minority carrier is holes.
  - (B) In N-type semiconductor material the majority current carrier is holes and the minority current carrier is free electrons.
  - (C) In P-type semiconductor material the majority current carrier is free electrons and the minority carrier is holes.
  - (D) In P-type semiconductor material the majority current carrier is holes and the minority current carrier is free electrons.
8. A junction diode is forward biased when the applied battery voltage is arranged so that:
- (A) the P material is positive and the N material is negative.
  - (B) the N material is positive and the P material is negative.
  - (C) the current carriers in the external circuit are holes.
  - (D) the barrier voltage is greater than the applied external voltage.
9. In this schematic symbol (  ) for a P-N junction, the arrow-head represents the: (Check two)
- (A) P material.
  - (B) N material.
  - (C) anode.
  - (D) cathode.
10. Germanium atoms and silicon atoms are similar, in that they:
- (A) have the same atomic number.
  - (B) have the same atomic weight.
  - (C) have the same number of valence electrons.
  - (D) are in the same "period" in the Periodic Table.

ENERGY DIAGRAM FOR CONDUCTOR

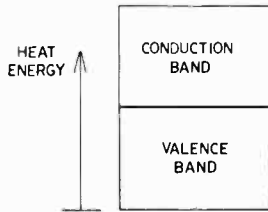


FIGURE 14(A)

ENERGY DIAGRAM FOR AN INSULATOR

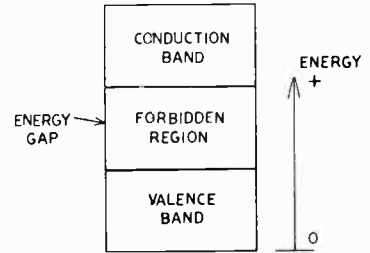


FIGURE 14(B)

ENERGY DIAGRAM FOR CONDUCTORS SEMICONDUCTORS AND INSULATORS

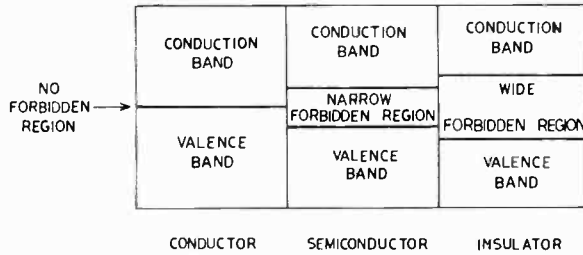


FIGURE 14(C)

N-TYPE GERMANIUM

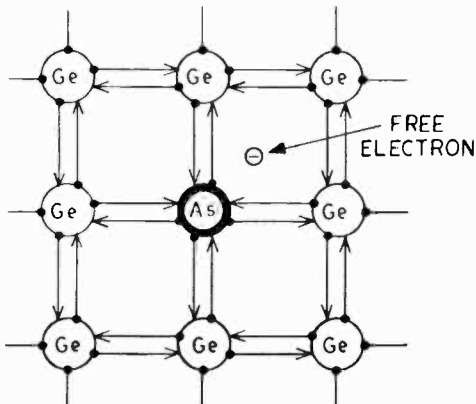


FIGURE 15

ENERGY DIAGRAM FOR N-TYPE SEMICONDUCTOR MATERIAL

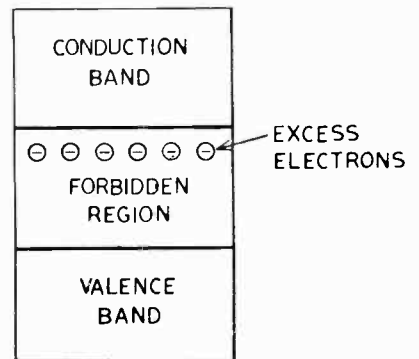


FIGURE 16

P-TYPE GERMANIUM

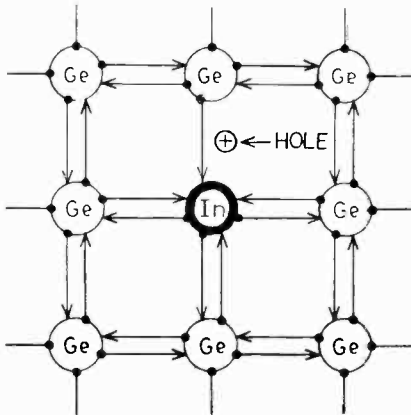


FIGURE 17

ENERGY DIAGRAM FOR P-TYPE SEMICONDUCTOR MATERIAL

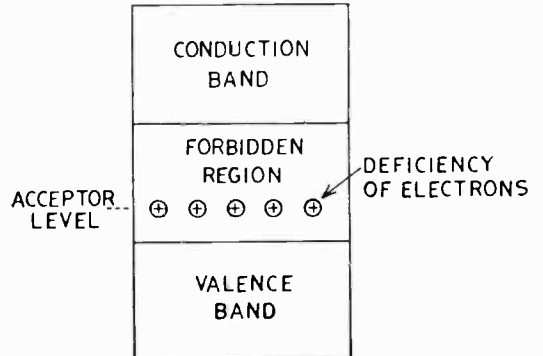


FIGURE 18

ELECTRON CONDUCTION IN N-TYPE SEMICONDUCTOR

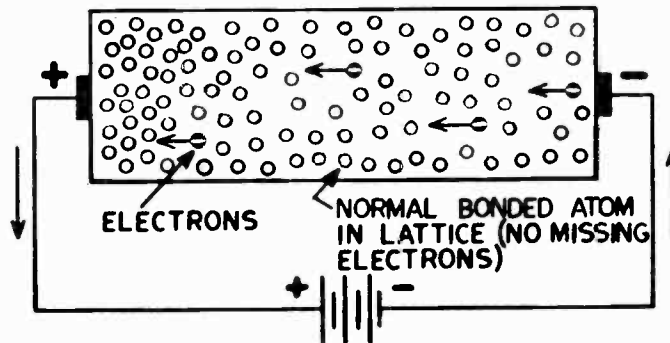


FIGURE 19(A)

HOLE CONDUCTION IN P-TYPE SEMICONDUCTOR

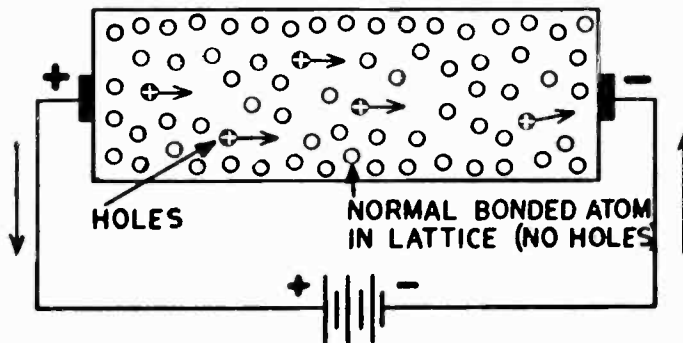
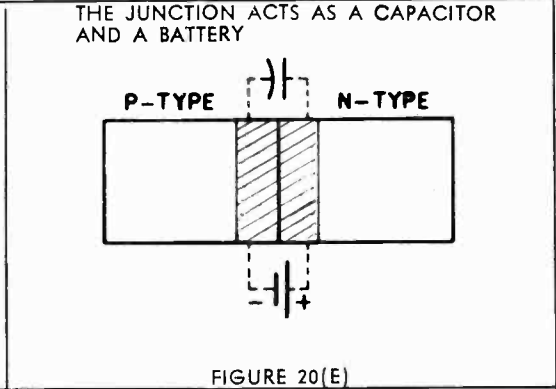
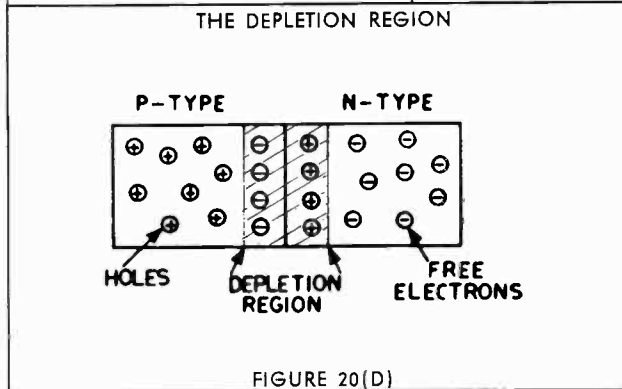
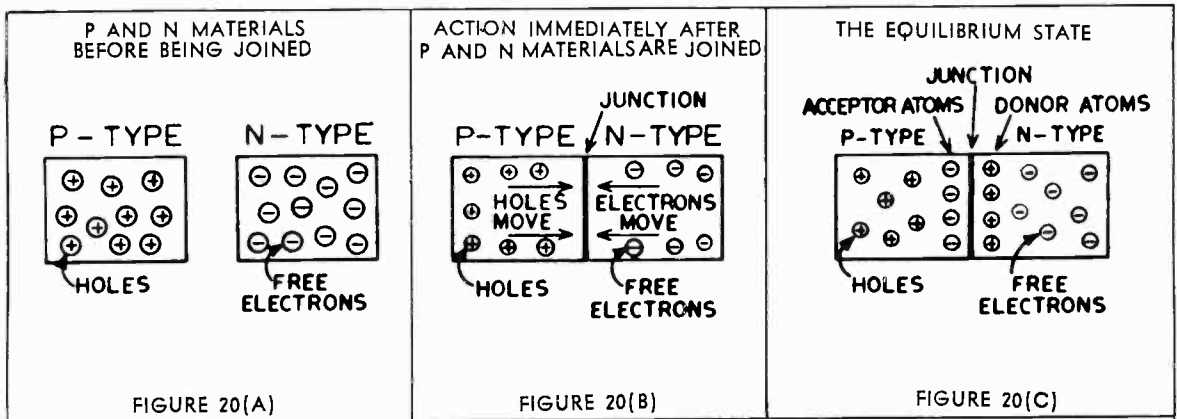
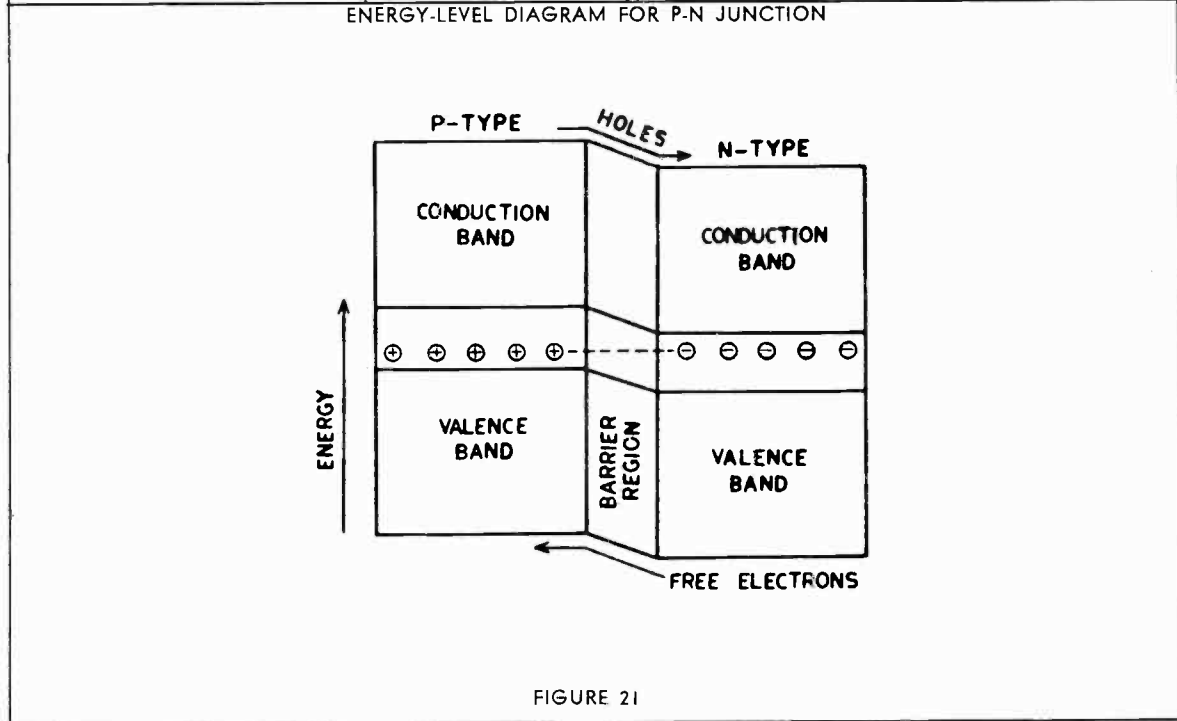


FIGURE 19(B)



ENERGY-LEVEL DIAGRAM FOR P-N JUNCTION



BIASING A P-N JUNCTION

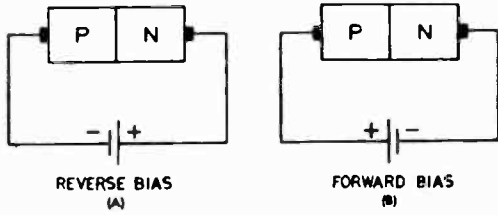


FIGURE 22

REVERSE BIAS

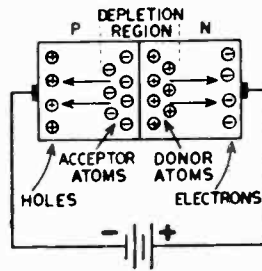


FIGURE 23(A)

FORWARD BIAS

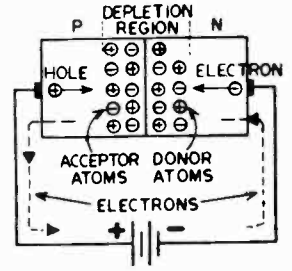
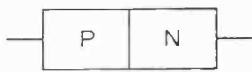


FIGURE 23(B)

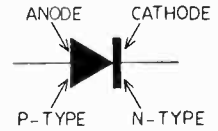
SCHEMATIC SYMBOLS



(A)



(B)

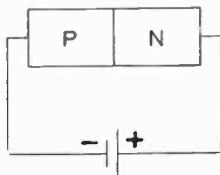


(C)

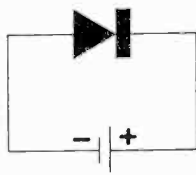
FIGURE 24

BIAS ARRANGEMENTS

REVERSE BIAS

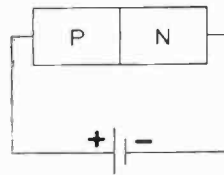


(A)

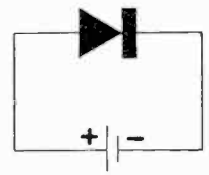


(B)

FORWARD BIAS



(C)



(D)

FIGURE 25

JUNCTION DIODES IN ELECTRONIC CIRCUITS  
POWER SUPPLY

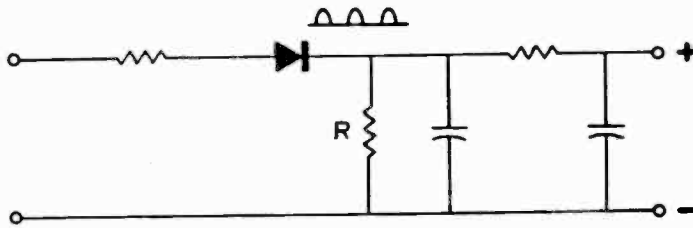


FIGURE 26(A)

DETECTOR

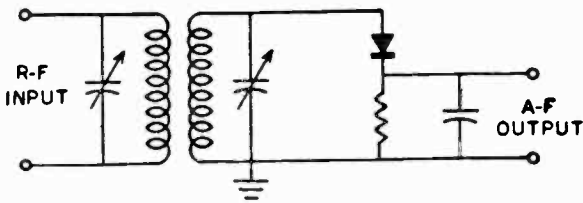


FIGURE 26(B)  
INPUT SIGNAL

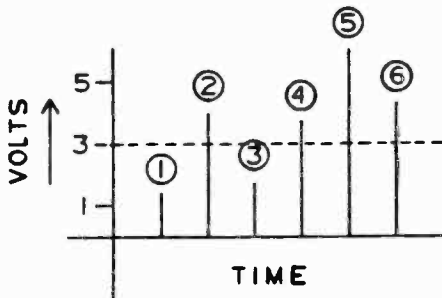


FIGURE 26(D)

CLIPPER

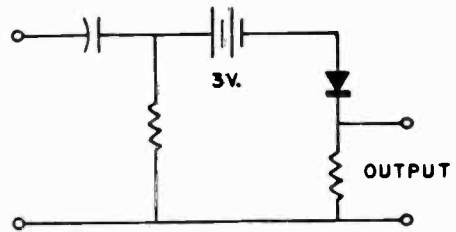


FIGURE 26(C)  
OUTPUT SIGNAL

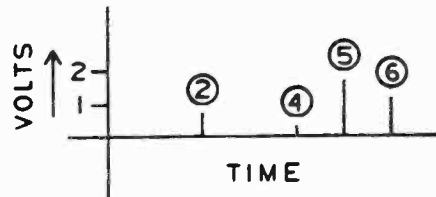


FIGURE 26(E)



THREE-DIMENSIONAL LATTICE IN DIAMOND

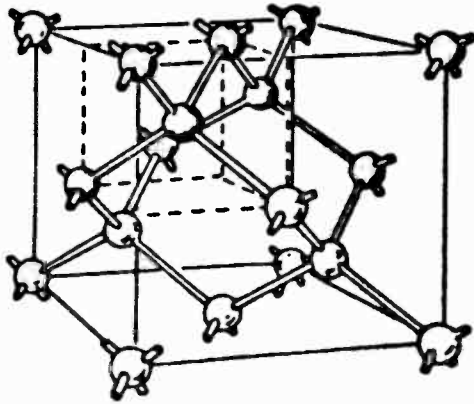


FIGURE 10

DIMENSIONAL VIEW OF CRYSTAL LATTICE IN GERMANIUM

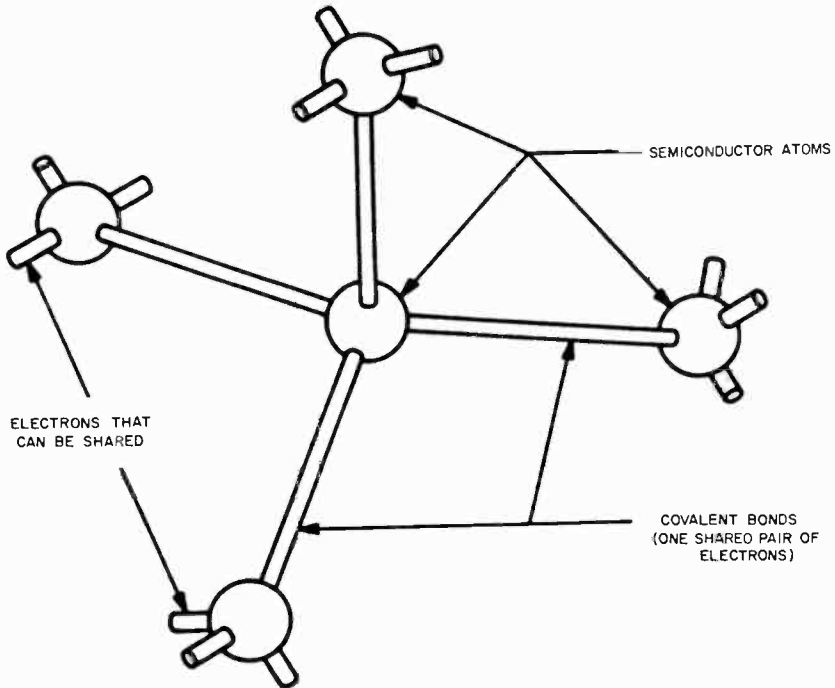


FIGURE 11

COVALENT BOND OF TWO GERMANIUM ATOMS

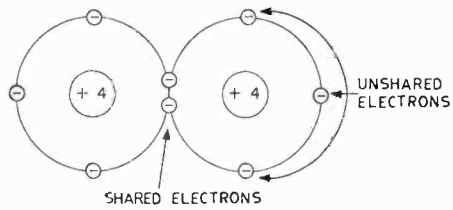


FIGURE 12(A)

COVALENT BOND OF FIVE GERMANIUM ATOMS

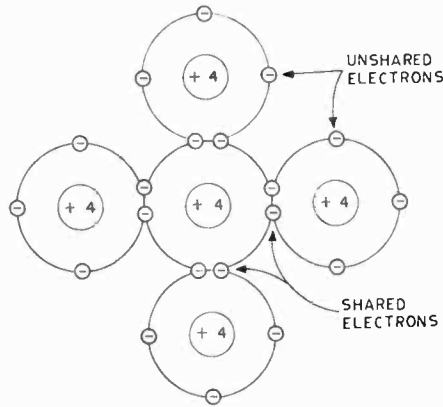
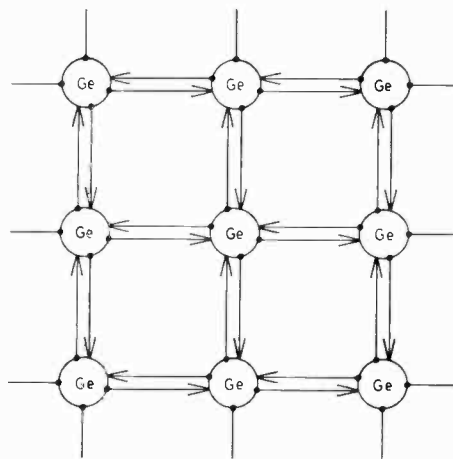


FIGURE 12(B)

CRYSTAL LATTICE OF INTRINSIC GERMANIUM SEMICONDUCTOR



Ge = GERMANIUM ATOMS

FIGURE 13

GERMANIUM ATOM

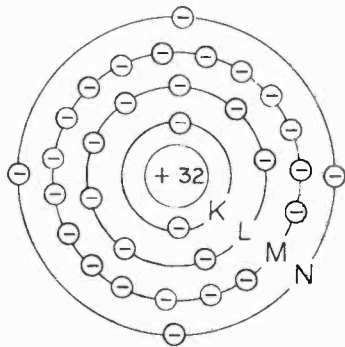


FIGURE 8(A)

CARBON ATOM

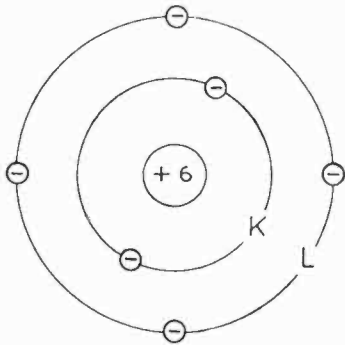


FIGURE 8(B)

SILICON ATOM

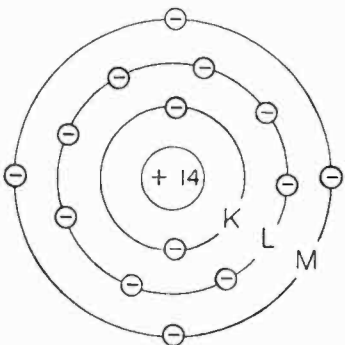


FIGURE 8(C)

GERMANIUM ATOM SUB-SHELL

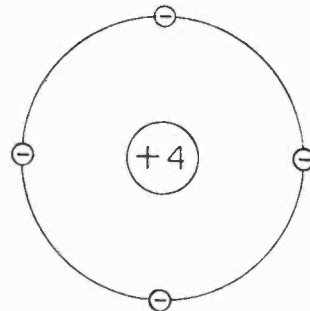


FIGURE 9(A)

SILICON ATOM SUB-SHELL

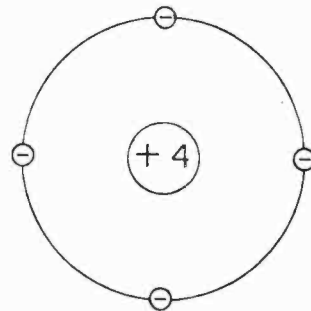


FIGURE 9(B)

# PERIODIC TABLE

Group	I	II	III	IV	V	VI	VII	VIII			0
Period	Mono-Valent	Bi-Valent	Tri-Valent	Tetra-Valent	Penta-Valent	Hexa-Valent	Hepta-Valent				Inert
1	1 Hydrogen										2 Helium
2	3 Lithium	4 Beryllium	5 Boron	6 Carbon	7 Nitrogen	8 Oxygen	9 Fluorine				10 Neon
3	11 Sodium	12 Magnesium	13 Aluminum	14 Silicon	15 Phosphorus	16 Sulfur	17 Chlorine				18 Argon
4	A 19 Potassium	20 Calcium	21 Scandium	22 Titanium	23 Vanadium	24 Chromium	25 Manganese	26 Iron	27 Cobalt	28 Nickel	
	B 29 Copper	30 Zinc	31 Gallium	32 Germanium	33 Arsenic	34 Selenium	35 Bromine				36 Krypton
5	A 37 Rubidium	38 Strontium	39 Yttrium	40 Zirconium	41 Niobium	42 Molybdenum	43 Technetium	44 Ruthenium	45 Rhodium	46 Palladium	
	B 47 Silver	48 Cadmium	49 Indium	50 Tin	51 Antimony	52 Tellurium	53 Iodine				54 Xenon
6	A 55 Cesium	56 Barium	57-71* Lanthanum	72 Hafnium	73 Tantalum	74 Tungsten	75 Rhenium	76 Osmium	77 Iridium	78 Platinum	
	B 79 Gold	80 Mercury	81 Thallium	82 Lead	83 Bismuth	84 Polonium	85 Astatine				86 Radon
7	87 Francium	88 Radium	** 89 Actinium								

\* LANTHANIDES

58 Cerium	59 Praseodymium	60 Neodymium	61 Promethium	62 Samarium	63 Europium	64 Gadolinium	65 Terbium	66 Dysprosium
67 Holmium	68 Erbium	69 Thulium	70 Ytterbium	71 Lutetium				

\*\* ACTINIDES

90 Thorium	91 Protactinium	92 Uranium	93 Neptunium	94 Plutonium	95 Americium	96 Curium	97 Berkelium	98 Californium
99 Einsteinium	100 Fermium	101 Mendelevium	102 Nobelium	103 Lawrencium				

FIGURE 7

CHLORINE ATOM

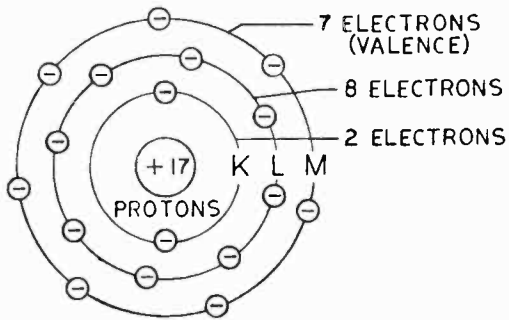


FIGURE 4(A)

SODIUM ATOM

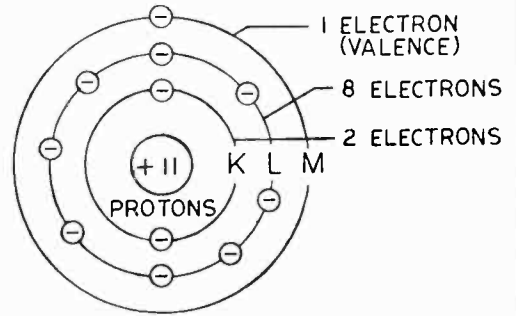


FIGURE 4(B)

POTASSIUM ATOM

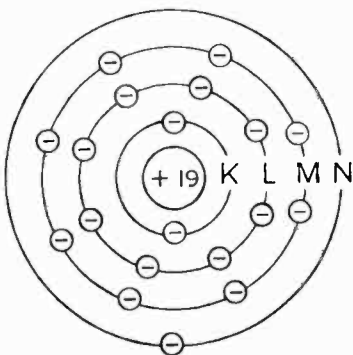


FIGURE 5(A)

COPPER ATOM

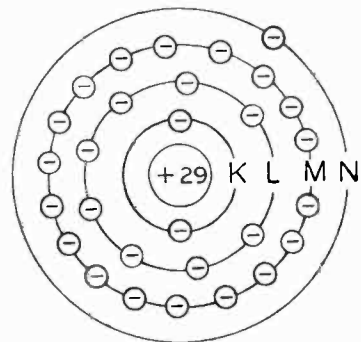


FIGURE 5(B)

SODIUM CHLORIDE

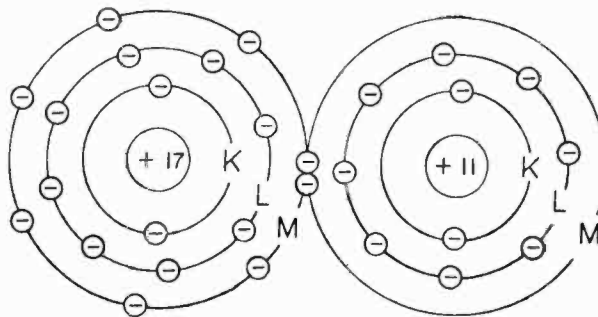


FIGURE 6

ATOMS

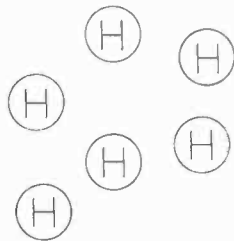
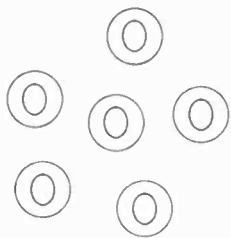
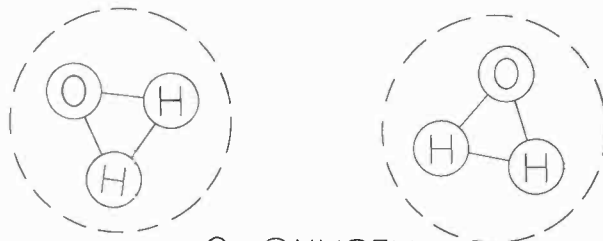


FIGURE 1(A)

MOLECULES



O = OXYGEN  
H = HYDROGEN

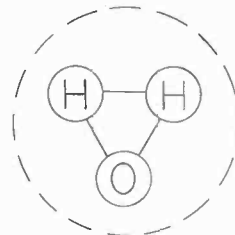
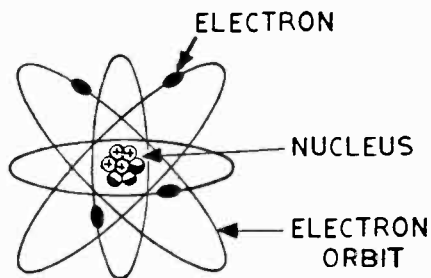


FIGURE 1(B)

THE ATOM



NOTE:

IN THE NUCLEUS

⊕ = PROTONS

● = NEUTRONS

FIGURE 2

HYDROGEN ATOM

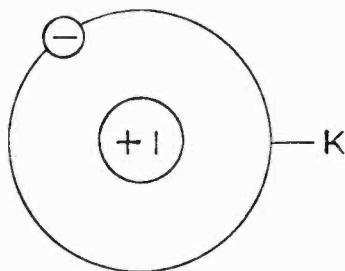


FIGURE 3(A)

HELIUM ATOM

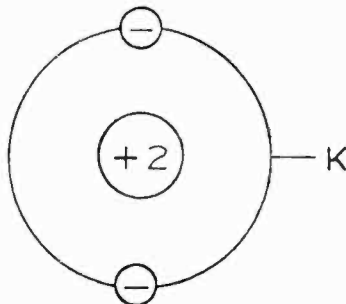


FIGURE 3(B)

LITHIUM ATOM

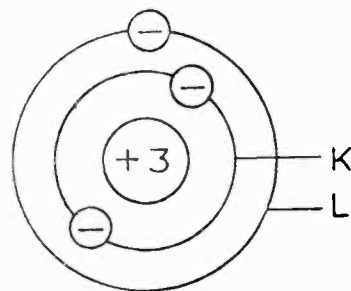


FIGURE 3(C)