training chart manual

SECTION J

FUNDAMENTALS OF SEMICONDUCTORS

Delco Remy

Delco Remy

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SECTION J

introduction

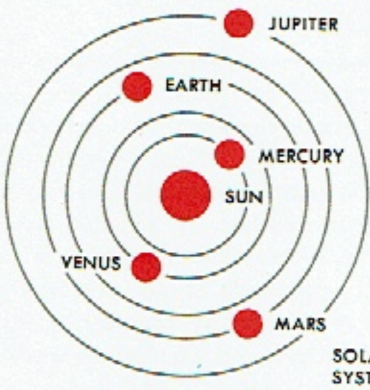
The fundamental operating principle of the semiconductor was first discovered in 1948. Since that time, hundreds of different types of semiconductor devices have been developed, and their use throughout the electronics industry has become widespread.

A semiconductor is an electrical device which acts as a conductor under certain conditions, and as a non-conductor or an insulator under other conditions. This manual covers (1) the fundamental principles of all semiconductors and (2) the operating principles of two kinds of semiconductors—diodes and transistors. Of the many different kinds of semiconductors, diodes and transistors are the two which are the most widely used in automotive-type electrical systems.

For the scientist and the engineer, a diode and a transistor can be a rather complex piece of equipment. But for those of us concerned with educational activities in the service field, the diode and transistor need not be complicated at all. Since the operating principles of semiconductors are basically quite simple, this manual has been prepared for the student and serviceman using basic, simplified explanations and illustrations.

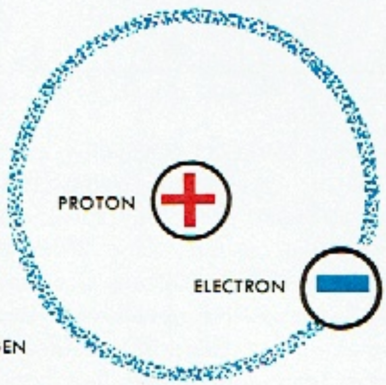
In the study of semiconductors, it is helpful to consider, briefly, the atomic structure of matter. All matter known to man is made up of tiny particles called molecules, and each molecule in turn is made up of one or more atoms.

An atom is an extremely small particle. It contains a nucleus or core consisting of protons and a number of rings in which electrons orbit around the core, much like the planets orbit around the sun.



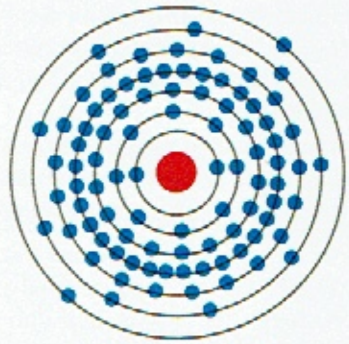
SOLAR SYSTEM

An atom of hydrogen is illustrated. Of the 92 natural elements, each having a different atomic structure, the hydrogen atom is the simplest. It has only one proton in its core and one electron in orbit around its core. The



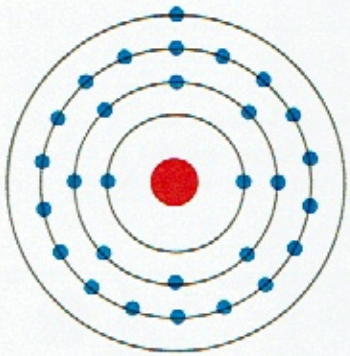
HYDROGEN ATOM

uranium atom is the most complex, with 92 protons in its core and 92 electrons in orbit around its core. Between these two elements are the remaining natural elements, each having a different number of protons and a matching number of electrons. It is this difference in the number of protons and electrons that causes the 92 elements to be different. Thus, hydrogen, a gas with one proton and



URANIUM ATOM

one matching electron per atom, is quite different from copper which is a solid containing 29 protons and 29 electrons.



COPPER ATOM

All of the 92 elements can be placed in numerical order according to their **atomic number.** The atomic number of an element represents the number of protons in the core. Thus, the atomic number of hydrogen is one, copper is 29, and uranium is 92.

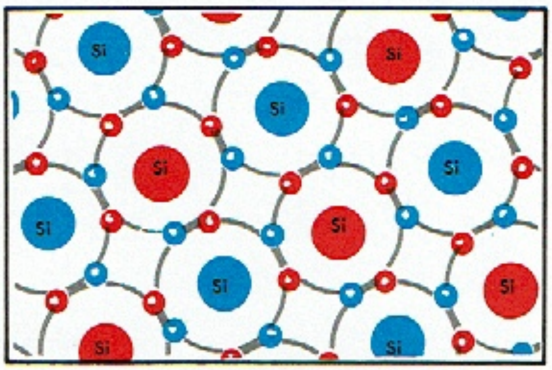
It is important to observe that all the electrons do not occupy the same path around the core. Instead, there are a number of paths, or rings, which are located at different distances from the core. The hydrogen atom has one ring, the copper atom four rings and the uranium atom seven rings.

It is the number of electrons in the **outermost** ring that is of special significance to us, because it is these electrons that determine the electrical characteristics of an element. Henceforth, we shall concern ourselves only with the **outermost** ring, which is often referred to as the **valence** ring.

If the number of electrons in the valence ring is **less** than four, the electrons are held to the core rather loosely, and can be made to move from one atom to another atom. Such an element is copper, which has only one electron in its valence ring. All materials which have less than four electrons in the valence ring are called conductors. The movement of electrons from atom to atom constitutes electric current.

If the number of electrons in the valence ring is **greater** than four, the electrons are held to the core rather tightly, and normally cannot be made to leave the atoms. Such an element or material is called an insulator. In any element, the number of electrons in the valence ring is never greater than eight.

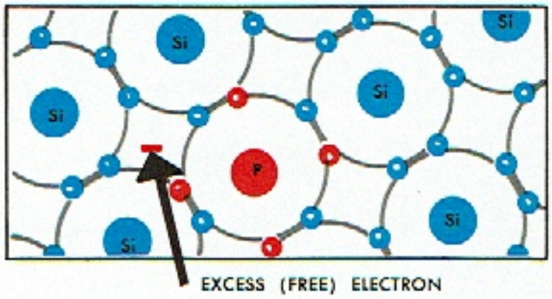
An interesting situation arises when the valence ring contains just four electrons. Certain elements of this type are of special interest because they are neither good conductors nor good insulators. Two elements having four valence ring electrons which are widely used in semiconductors are silicon and germanium. Silicon will be discussed in this section and germanium in a following section.



COVALENT BONDING

When a number of silicon atoms are combined in crystalline form, the result is called covalent bonding. This means that the electrons in the valence or outer ring of one silicon atom join with the outer ring electrons of other silicon atoms so that the atoms share electrons in the valence ring. It can be seen that each atom effectively has eight electrons in its outer ring making the outer ring complete. This makes the material a very good insulator since there are more than four electrons in the outer rings.

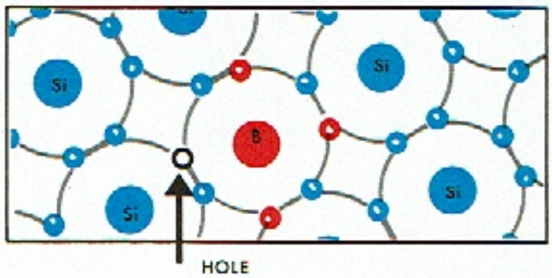
When certain other materials are added to the silicon crystal in highly controlled amounts, the resultant mixture is said to be



EXCESS (FREE) ELECTRON

"doped." The new material is no longer a very good insulator, and it possesses some unusual electrical properties.

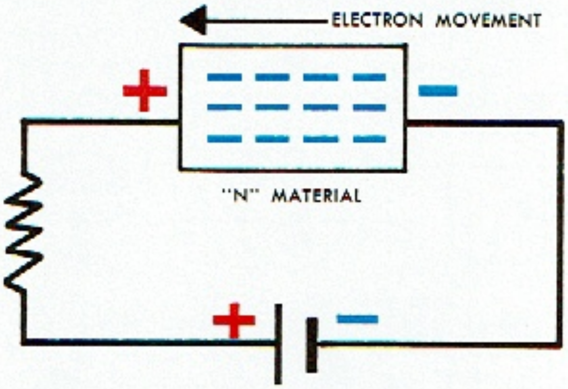
Two elements commonly used to dope the silicon crystal are phosphorus and antimony. Both of these elements have five electrons in their valence ring. When phosphorus, for example, is combined with silicon, covalent bonding occurs but there is one electron left over. This electron is called a "free" electron, which can be made to move through the material very easily. Any material having an extra electron is called negative type or "N" type material.



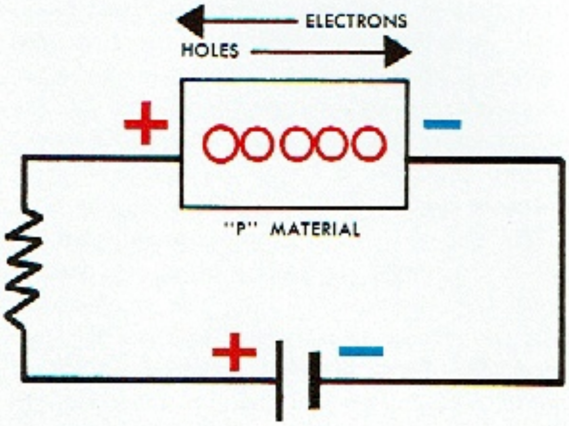
HOLE

Two other elements commonly used to dope the silicon crystal are boron and indium. These elements have only three electrons in their valence or outer ring. When boron, for example, is added to silicon, covalent bonding occurs around the nucleus or core of the boron atom but there is a deficiency of one electron for complete covalent bonding. The resultant void is called a **hole.** While the electron is well known as a negative charge of electricity, the hole can be considered as a positive charge of electricity. Materials of this type are called positive or "P" type material.

In order to understand semiconductors, it is necessary to look upon the hole as a positive current carrier, just like the electron is a negative current carrier. The hole can effectively move from atom to atom, just like an electron can move from atom to atom.

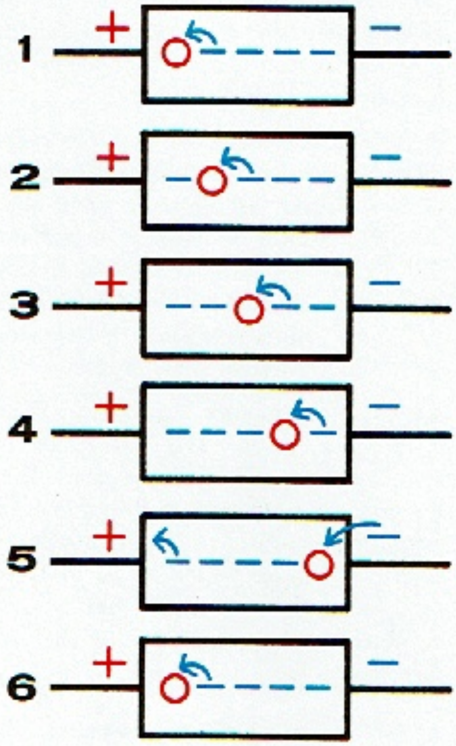


When a source of voltage, such as a battery, is connected to "N" type material (material having an excess of electrons) as illustrated, an electron current will flow through the circuit. The current flow in the "N" type semiconductor consists of a movement of the "free" electrons through the material. This type of current flow in the semiconductor is very similar to that which occurs in a copper wire.



When a battery of sufficient voltage is connected to "P" type material (a material having a deficiency of electrons), a current also will flow through the circuit, but the current in the "P" type semiconductor is looked upon as a movement of the positively charged holes. This hole movement can be explained as follows, with reference being made to the simplified illustrations of the "P" type material.

Since it is a fact in electricity that like charges repel and unlike charges attract, the positive battery voltage will attract electrons in the "P" material to the positive battery connection at the semiconductor. Similarly, the negative potential of the battery will repel electrons from the negative battery connection. An elec-



tron from one of the covalent bonds of a doping atom will move to the left toward the positive terminal, and will fill one of the holes near the terminal. This movement of an electron leaves behind a hole. The positively charged hole, then, has moved to the right, toward the negative terminal of the battery. Another electron will then move in to fill this hole, creating another hole nearer the negative terminal. This process continues, and in this manner the hole continues to move to the right, until it arrives in the vicinity of the negative connection at the semiconductor. At this time, the hole is filled by an electron which leaves the negative wire connected to the semiconductor, and the positive wire removes an electron from the semiconductor. The process is then ready to repeat as described above.

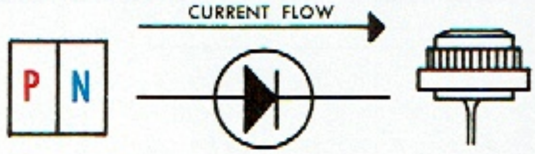
The continuous movement of holes from the positive terminal to the negative terminal can be looked upon as current flow in "P" type material, and occurs when the battery voltage causes the electrons to shift around in the covalent bonds. It is important to note that the hole movement occurs only within the semiconductor, while electrons flow through the entire circuit. The hole movement theory affords an easier way to an understanding of how diodes and transistors operate, as will be seen in the succeeding chapters.

It is of interest to note that the manufacture of semiconductors requires techniques that are most exacting. To illustrate this, the ratio of crystal material to doping material is often ten million parts to one. Also, the silicon or germanium crystal is refined to a state of purity having only a few parts of impurity to over one billion parts of pure crystal.

All semiconductors used in Delco-Remy equipment must meet the most exacting specifications, and are very carefully designed to provide optimum performance under all operating conditions. Since diodes and transistors are more widely used in Delco-Remy equipment than are any other types of semiconductors, the remainder of this manual is devoted to these two types.

diodes

A diode is an electrical device that will allow current to pass through itself in one direction only. The symbol for a diode is shown, with conventional current flow allowed only in the direction of the arrow.



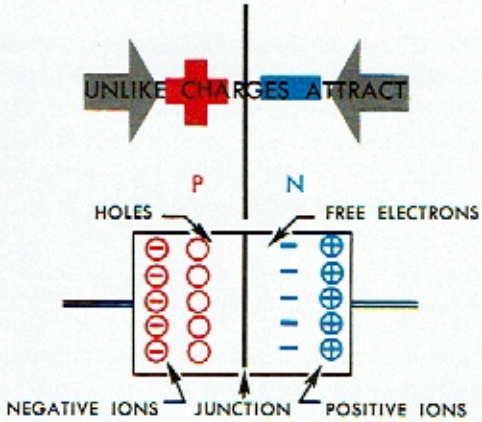
DIODE SYMBOL

ELEMENT	ATOMIC NUMBER	NUMBER OF PROTONS	NUMBER OF ELECTRONS	VALENCE RING ELECTRONS
Boron (B)	5	5	5	3
Silicon (Si)	14	14	14	4
Phosphorus (P)	15	15	15	5

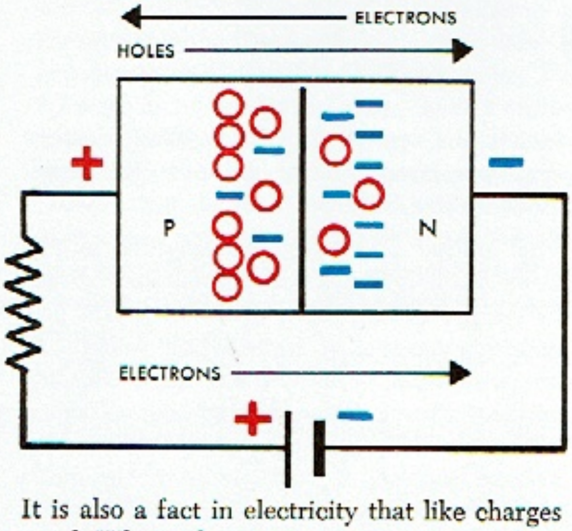
A diode is formed when one section of a semiconductor material is formed into "N" type material, and an adjoining portion is formed into "P" type material. The process of forming the two types of material involves not just a mechanical junction, but a carefully controlled manufacturing technique which creates the two parts in a diffusion process. The process involves a wafer of silicon, about .007 inch thick and 1½ inches in diameter, which is painted on one side with a solution containing phosphorus pentoxide, and on the other side with a solution containing boric oxide. The painted wafer is then placed in a furnace containing a hydrogen atmosphere at 1200°C approximately. The compounds (phosphorus pentoxide and boric oxide) are chemically reduced, and boron and phosphorus diffuse into the silicon wafer to form "P" type and "N" type material, respectively. The wafer is then plated to facilitate the soldering of electrical connectors, and broken into small pieces before being incorporated into the diode case assembly. In diodes, the "N" material is usually phosphorus doped silicon and the "P" material usually is boron doped silicon.

operating principles

The following explanations use the previous chapter as a basis for discussion on diodes.



It is a fact in electricity that unlike charges attract. This means that negative and positive charges have a mutual attraction for each other. When "N" material and "P" material are formed, an attraction exists between the electrons and holes, and it would seem that the electrons would drift across the junction area and fill the holes in the "P" material. This does happen, but only to a very limited extent. As the electrons drift toward the junction area, they leave behind charged particles called positive ions. An ion is an atom having a deficiency or excess of electrons. These positive ions exert an attractive force on the remaining free electrons, and prevent additional electrons from crossing the junction. In a similar manner, the holes leave behind negative ions which exert an attractive force on the remaining holes to prevent them from crossing the junction. The net result is a stabilized condition **with a deficiency of electrons and holes at the junction area.**

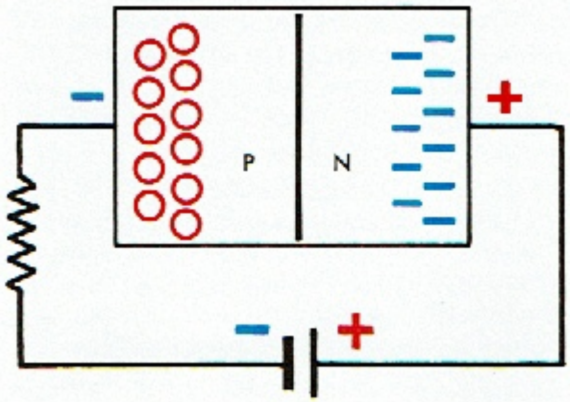


It is also a fact in electricity that like charges repel. When a battery is connected to a diode as illustrated, the negative battery voltage will repel the electrons in the "N" material, and the positive battery voltage will repel the holes in the "P" material. With sufficient voltage, electrons will move from the negative terminal of the battery across the junction area to the positive battery terminal to constitute current flow. Also, the positive holes, in effect, will move through the "P" material through the junction area in the manner described in the preceding chapter.

As the electrons move from the "N" material to the "P" material, the battery will inject electrons into the "N" material and attract electrons from the "P" material to maintain a given rate of electron movement. The circuit, then, has electrons moving around the circuit in a manner to constitute current flow. The important thing to observe, however, is that in order for an appreciable amount of current to flow through the semiconductor, there must be a concentration of holes in the "P" material near the junction, and a concentration of electrons in the "N" material near the junction. This is true because for electrons to move into the "P" material, there must be holes present at the junction **into which the electrons can move.** If there are no holes present, the electrons have no place to go in the "P" material, and no current will flow.

The circuit arrangement illustrated, with the battery negative terminal connected to the "N" type material and the battery positive terminal connected to the "P" type material, is known as a **forward bias** connection. The repelling action of the battery voltage causes electrons and holes to congregate at the junction area in large numbers—this is the condition necessary for current flow through a diode.

Now let us see what happens when the battery connections are reversed. As illustrated, the positive battery potential will attract the electrons away from the junction area in the "N" type material, and the negative battery potential will attract the holes away from the junction area in the "P" material. The electrons and holes merely drift away from the junction area; they do not enter the circuit to constitute current flow. With the junction area void of current carriers (electrons and holes)



there will be no current flow. In effect, a very high electrical resistance is created at the junction area. This type of battery connection is referred to as **reverse bias,** which causes the diode to block current flow.

The operating principles of a diode can be summarized in these two statements:

1. The diode will allow current to flow if the voltage across the diode causes electrons and holes to congregate at the junction area. (Forward Bias)
2. The diode will not allow current to flow if the voltage across the diode causes the junction area to be void of electrons and holes. (Reverse Bias)

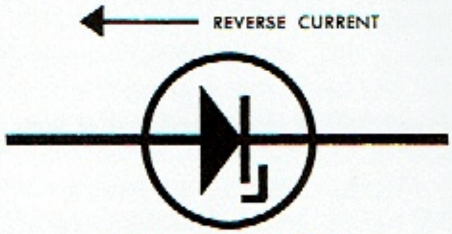
Let's repeat a statement already made in this chapter. For electrons to move into the "P" material, there must be holes present in the "P" material near the junction **into which the electrons can move.** The reason for the hole theory now becomes more apparent, as this theory provides a convenient means of explaining how a diode blocks or prevents current flow.

diode leakage current

When a reverse bias voltage is connected to a diode, it may be true that a small current will flow through the diode in the reverse direction, but the reverse current is very, very small in magnitude. If the voltage across the diode is increased, a value eventually will be reached called the **maximum reverse voltage** of the diode. At this voltage value, the covalent bond structure will break down and a sharp rise in reverse current will occur. If the reverse current is sufficient in magnitude and duration, the diode will be damaged due to excessive heat. Diodes are selected, of course, with an adequate maximum reverse voltage rating so that damaging reverse currents will not normally occur during operation.

zener diode

The zener diode is a specially designed type of diode that will satisfactorily conduct current in the reverse direction. The primary feature of this type of diode is that it is very heavily doped during manufacture—the large number of extra current carriers (electrons and holes) allows the zener diode to conduct cur-



ZENER DIODE SYMBOL

rent in the reverse direction without damage if proper circuit design is used. The zener diode symbol is shown.

The unique operating characteristic of the zener diode is that it will not conduct current in the reverse direction below a certain predetermined value of reverse bias voltage. As an example, a certain zener diode may not conduct current if the reverse bias voltage is below six volts, but when the reverse bias voltage becomes six volts or more, the diode suddenly conducts reverse current. This type of diode is used in control circuits.