THE TRANSISTOR RADIO HANDBOOK

-Theory
-Circuitry
-Equipment

THE TRANSISTOR RADIO HANDBOOK

(First edition)

– Theory
– Circuitry
Equipment

by Donald L. Stoner and L. A. Earnshaw

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THE TRANSISTOR RADIO HANDBOOK

1st EDITION

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FOREWORD TO THE FIRST EDITION

In all probability this is the first transistor manual written by two authors in two widely separated countries. Transistors are transistors the world over, and in each country they function the same.

Different environments engender different ideas, however. One cannot imagine an Eskimo inventing a plow, a Bolivian inventing a kayak, or an American inventing a set of chopsticks. However, if one gave an American a set of chopsticks and said "Improve on these," no doubt he would.

Through the medium of amateur radio, the authors have discussed the subject of transistors back and forth across the Pacific ocean. We sincerely hope that the synthesis of our ideas have produced worthwhile results. While we make no claim to having invented a new kind of plow or a better kayak, we do feel that by adding small bowls to the ends of the chopsticks and calling them spoons, we have improved on something. Bowls are not new, nor are chopsticks, but a combination of both is a very useful tool.

The authors particularly wish to thank the following individuals and companies who have provided assistance and encouragement in this project.

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Mr. William Wilson	*International Rectifier Corp.*
Mr. C. D. Simmonds	*Philco Semiconductors*
Mr. Frank O'Brien	*Pacific Semiconductors*
Mr. John Fischer	*Radio Corporation of America*
Major Gilbert	*Texas Instruments*

CHAPTER ONE

Inside Semiconductors

The reader need not understand all the mysteries pertaining to holes, covalence bonds, etcetera, to construct transistor circuits and equipment. All that is needed is a good magazine article and a few clear photos. However, this basic information is essential either to troubleshoot equipment properly or to design circuits yourself. If you are content to follow the leader, omit this chapter.

Before delving into the operation of a transistor, it would be useful to review a bit of high school chemistry regarding the nature of *matter*.

1.1 What is Matter?

That's simple. Matter is just about everything! Typical examples are the air we breathe, the water we drink, and the food we eat. These examples also illustrate the three basic forms of matter: gaseous, liquid, and solid. Matter may be found in these forms as either *elements* or *compounds*. An element is defined as a basic structure which cannot be separated into substances of other kinds. Scientists have been able to isolate over 100 elements. Some of the more familiar ones are copper, aluminum, hydrogen, and oxygen. Lesser known elements, which we shall study later, including silicon and germanium.

A compound, on the other hand, is a pure substance which contains two or more elements and has a constant composition. It usually exhibits properties different from the elements of which it is composed. A very abundant compound is water. It is composed of two parts hydrogen and one part oxygen and is known by chemical shorthand as H_2O.

The Molecule Elements are thought to be composed of *molecules*. A molecule is the smallest physical part of an element or compound. If one divides a piece of copper many times into the smallest part possible and still has copper, this small part would be a molecule.

The Atom Scientists believe that molecules are constructed of various arrangements of atoms. The molecule may contain one or more like atoms in an element or two or more different atoms in a compound. Figure 1.1-A shows the relationship between the atom and the molecule. Two of the simple hydrogen atoms combine with a single atom of oxygen to form one molecule of the compound water.

Since there are over 100 elements, it is reasonable to expect that there exist the same number of atomic structures which correspond to these elements. As will

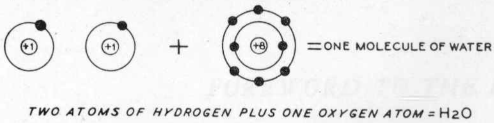


Figure 1.1-A
THE RELATIONSHIP BETWEEN ATOMS AND MOLECULES

soon be shown, the atom is made up of *subatomic particles.* The same particles make up all the atoms in the universe. Only the manner in which they are arranged varies, and it is the arrangement which gives each atom its own characteristics. This may be easier to comprehend if one compares the atom to a fingerprint. The fingerprint is composed of simple loops and whirls, but they can be combined in an infinite number of ways, and no two fingerprints are alike! Criminologists are convinced that all the fingerprint types in the world have *not* been discovered. Similarly, scientists assume that there are more elements which have not been identified.

1.2 Building Blocks of the Universe

For the purpose of illustration, let the reader equip himself with a more powerful microscope than exists in the world. With the microscope, examine a piece of aluminum. Aluminum is usually associated with chassis and panels. It is smooth and

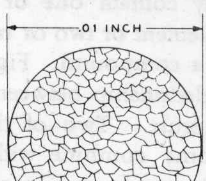


Figure 1.2-A
CRYSTALLINE SURFACE OF ALUMINUM

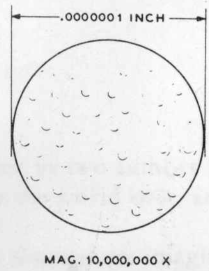


Figure 1.2-B
VAGUE OUTLINE OF THE ATOMIC STRUCTURE OF ALUMINUM

shiny, and may be drilled, punched and formed into angles. If, however, the surface is magnified 100 times, it becomes obvious that the aluminum is not smooth, but actually has a rough crystalline surface as shown in figure 1.2-A.

If the surface is magnified 10 million times, one begins to see vague outlines of roughly spherical shape. These tiny blobs are the atoms of aluminum, and may be "seen" in figure 1.2-B.

No one has seen an atom. However, with X-ray techniques and advanced mathematics, it is possible to make some rather accurate guesses about their appearance. Scientists believe the atom looks like the drawing in figure 1.2-C. It consists of a central core with one or more tiny particles orbiting around it as planets orbit the sun in the solar system.

To simplify explanations and drawings,

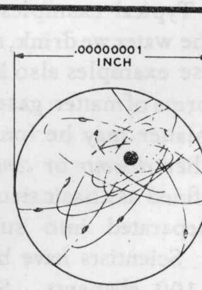


Figure 1.2-C
SCIENTISTS BELIEVE THE ATOM LOOKS LIKE THIS.

the atom is usually depicted as shown in figure 1.2-D; in this case it is the "chemical schematic" of an atom of aluminum. Notice that this atom of aluminum is more complex than the hydrogen atom shown in figure 1.1-A.

Composition of the Atom Referring to figure 1.2-D, the central core of the atom is termed the *nucleus.* If it were possible to examine the nucleus of the aluminum atom under the imaginary microscope, one would see something similar to figure 1.2-E. The nucleus is composed of *neutrons* with *no charge* and *protons* which have a positive *charge.* These components make up the heart of the atom. Note in figure 1.2-D that the nucleus of the atom consists of 13 protons and 14 neutrons.

Each of the tiny particles orbiting the nucleus is a negatively charged *electron.* The electrons whirl at tremendous speeds around the nucleus in orbits or *rings*, as they are more commonly called. Note further that the aluminum atom has two electrons in the first ring, eight in the second, and three in the outer ring, for a total of 13 electrons.

Size It might be helpful to describe these particles in definite terms. The diameter of an electron is believed to be 0.00000000000022 or 22×10^{-14} inches and is about three times the size of the proton. Despite its smaller size, the mass of the proton is about 1,850 times that of the electron. The comparison is something like a cubic foot of lead to a cubic foot of feathers.

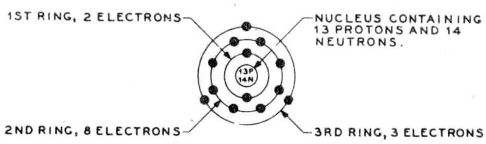


Figure 1.2-D
A SINGLE ATOM OF ALUMINUM

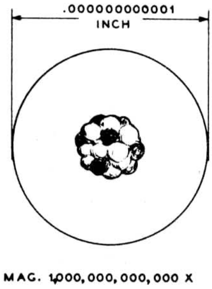


Figure 1.2-E
THE NUCLEUS OF THE ATOM IS BELIEVED TO LOOK LIKE THIS
It contains both positive protons, and neutrons which have no charge.

If you can comprehend a copper penny being enlarged to the size of the earth's orbit around the sun, then you would be able to visualize the electrons in the copper. They would be roughly the size of baseballs and might be spaced approximately three miles apart! The nucleus, the central "sun," would be composed of a group of neutrons and protons about the size of walnuts!

All matter is composed of atoms. By the same token, all atoms are built up from electrons, neutrons, and protons. Only the way in which the parts are arranged and their quantities will differ. Thus, these particles may be considered the fundamental building blocks of the universe.

Charges The positive charge on the proton and the negative charge on the electron are exactly equal in the aluminum atom discussed earlier. The 13 protons equal the 13 electrons, and this aluminum atom is said to be *electrically balanced.*

These charges are believed to be the smallest that exist, and therefore they are considered the fundamental unit of electrical charge. However, this quantity is much too small to deal with, and the coulomb is commonly used in its place. One coulomb of electricity contains more than six million, million, million, or 6.28×10^{18} electrons!

1.3 Atomic Structure

The most important feature of the atom is the fickle outer ring of electrons. The atom is somewhat similar to the common household onion in that it is composed of many rings. It is relatively easy to remove pieces of the outer ring simply by peeling them off. The inner rings do not fall off, for the outer rings hold them in place.

The inner rings of the atom are tightly bound to the nucleus, but the outer ring may be stripped off. More commonly, subtle modifications are made to change its characteristics.

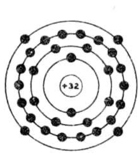
It is also known that the electrons in the outer ring may skip from one atom to another in a random manner due to thermal agitation (heat). Also, electrons may be added or removed from the outer ring. Electrons able to move in this manner are known as *valence electrons*. Any matter with a large number of valence electrons is known as a *conductor*, and matter which has few loosely held electrons is termed an *insulator*. Materials referred to as *semiconductors* lie somewhere between these two extremes. Germanium and silicon are two excellent examples of semiconductors. These two elements are not very good conductors in their pure states. When properly modified they can be made to conduct electricity, much the same as a piece of wire.

The atomic schematics for germanium and silicon are shown in figure 1.3-A and 1.3-B, respectively. For simplicity, the neutrons found in the nucleus are not shown. Since neutrons have no charge, they do not affect our discussion. Note also the similarity between the germanium and silicon atoms. Each atom has four valence electrons in the outer ring. Since the action occurring in the atom takes place in the valence ring, the atomic schematic may be further simplified by showing only the valence electrons, as in figure 1.3-C. When reduced to this form, both germanium and silicon appear to be identical, and as a matter of fact they are equally useful in manufacturing transistors.

The reader should understand that different materials may contain a different number of valence electrons. However, just because two atoms contain the same number of valence electrons, they do not necessarily constitute the same material. Note that in aluminum the valence ring contains three electrons, as does gallium, which is also used in manufacturing semiconductor products. Two other elements useful in preparing semiconductors are antimony and arsenic, each having five valence electrons.

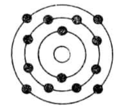
1.4 Crystal Lattice Structures

Most substances when examined under a microscope will exhibit a crystalline structure, even though the surface may appear smooth to the eye. All crystalline sub-



1ST RING – 2 ELECTRONS
2ND RING – 8 ELECTRONS
3RD RING – 18 ELECTRONS
4TH RING – 4 ELECTRONS

Figure 1.3-A
GERMANIUM ATOM (Ge)



1ST RING – 2 ELECTRONS
2ND RING – 8 ELECTRONS
3RD RING – 4 ELECTRONS

Figure 1.3-B
SILICON ATOM (Si)

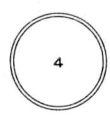


Figure 1.3-C
A SIMPLIFIED DRAWING SHOWING ONLY THE VALENCE ELECTRONS
This could be either the germanium or silicon atom since they both have four valence electrons.

stances have an identifying characteristic. The most common example would be the elusive snowflake, which is composed of an infinite number of geometric patterns made up of 60° angles. Common household salt will form tiny cubes, while some materials form needles, rhomboids, or variations of hexagonal or rectangular structures.

By scientific deduction, it appears that the rotation of the valence electrons in one atom is closely coordinated to the electron motion in adjacent atoms. The coordinated rotation forms an *electron pair bond* or a *covalence bond*. This bond is countermanded by the repulsion of the positively charged nucleus and a state of equilibrium exists, forming a single crystal of the material.

The lattice structure of a single germanium crystal is shown in figure 1.4-A. For simplicity, only one "layer" of the structure is shown. Although it is not possible to illustrate the fact with two dimensional drawing, each germanium atom is bonded by electron pairs to *four* adjacent atoms (or would be if an infinite number could be illustrated). This is due to the fact that each atom contains four electrons in the outer or valence ring.

In the element copper, the valence electrons are not tightly bound as just described, but are free to move about. Thus, when subjected to an electric potential, the valence electrons move in an orderly manner. Such material is said to be a good conductor. On the other hand, material

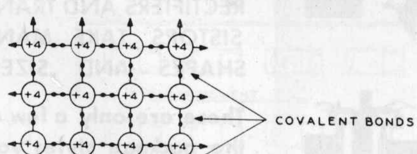


Figure 1.4-A
A STABLE LATTICE STRUCTURE CONTAINING ONLY GERMANIUM OR SILICON ATOMS.

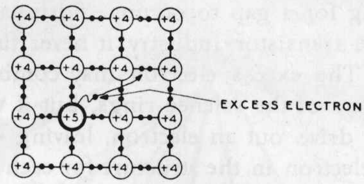


Figure 1.5-A
A "DONOR" IMPURITY HAS BEEN ADDED TO THE PURE GERMANIUM INTRODUCING AN EXCESS ELECTRON

like polystyrene is a poor conductor, and examination shows that its valence electrons are very tightly bound together.

1.5 Impurities

Earlier it was stated that silicon and germanium could be made into conductors by modifying their structure. These structures were considered to be *pure*, that is, containing nothing but germanium or silicon atoms. To be usable in semiconductors, germanium and silicon must be *refined* to the point where only one impurity will be found in 10 billion parts of the pure material.

When this state of purity is achieved, a controlled amount of *impurities* may be added to modify the structure in a desired manner. Such impurities might be antimony, arsenic, aluminum, or the gallium mentioned earlier.

A typical example might be the pure germanium structure discussed in section 1.4. Impurities "dope" the element by adding one part antimony (five valence electrons) to 10 million parts of germanium. An examination of the germanium structure now will show an extra atom in the group (figure 1.5-A0, a single atom of antimony. A closer look will show that the atom is accompanied by an excess electron. Remember that germanium has four valence electrons, while antimony has five. Since there can be no more than four electrons in any of the valence rings, this excess electron must drift through the structure looking for a gap to occupy. Fortunately for the transistor industry it never finds one! The excess electron may combine with one of the valence rings, but it will always drive out an electron, leaving one extra electron in the structure for each excess electron added.

The impurity that has donated the extra electron is logically called a *donor impurity*. Arsenic could also be the donor since it has one extra electron when compared to germanium or silicon. Although the discussion has dealt with single structures and a single excess electron, the reader should be aware that millions of these excess electrons are present in millions of lattices, even in a piece of germanium too small to be seen with the naked eye.

Germanium to which a donor impurity has been added is called *N-type* germanium, since it contains an excess of electrons which carry a negative charge.

Acceptors Just as we have added the antimony and arsenic impurities, it is possible to "contaminate" pure germanium with aluminum or gallium. As mentioned earlier, these two impurities have only three valence electrons. What happens to the atomic structure when these impurities are combined with the germanium or silicon? There is no longer an excess of electrons, but rather a lack of them. Thus, this impurity is able to accept electrons from the germanium, leaving a *hole* in the valence rings. This type of impurity is referred to as an *acceptor impurity*.

To illustrate what might happen in a single crystal of germanium when "doped" with acceptor impurities, refer to figure 1.5-B. The impurity atom might withdraw an electron from the adjoining germanium atom in a futile effort to neutralize the

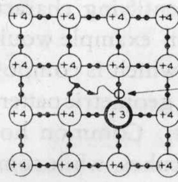
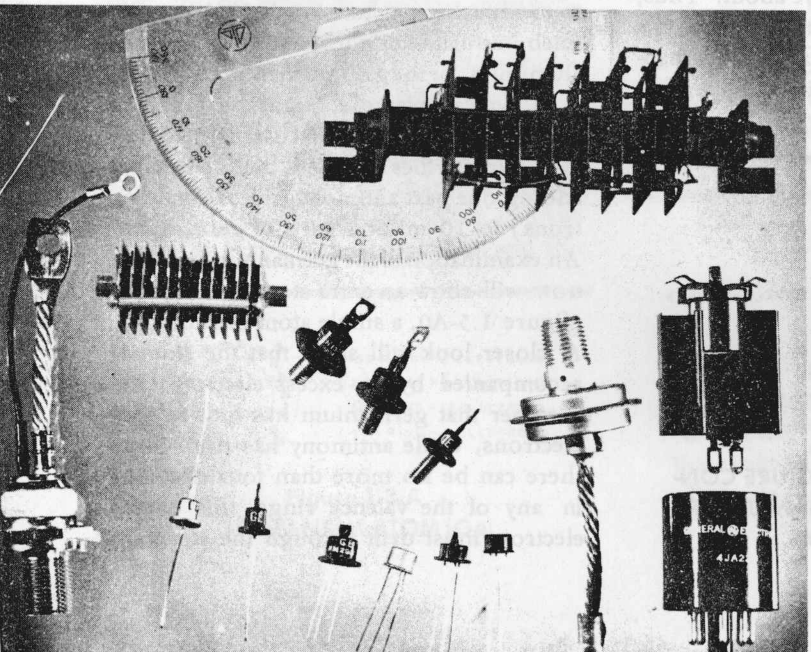


Figure 1.5-B

AN "ACCEPTOR" IMPURITY IS SHOWN ADDED TO PURE GERMANIUM

Valence electrons try to fill this space, but a gap always remains in the structure.



SEMICONDUCTOR RECTIFIERS AND TRANSISTORS TAKE MANY SHAPES AND SIZES.

These are only a few of the package styles you will find in electronic equipment. (Courtesy, General Electric Company)

structure. However, this leaves a gap in the adjacent atom's valence ring which might be filled. Our incomplete atom is compelled to become whole again and it, in turn, withdraws an electron from another atom. This occurs continuously, and in a random manner. The hole is simply a gap in a valence ring, which has no electron to fill it. Since there is continuous agitation in the structure (due to ever-present heat) the gap or hole is continuously changing position. As before, there are millions of these impurity atoms in a tiny speck of germanium, and, consequently, there are also millions of holes seeking an electron. Although the holes are moving, they are evenly distributed and never leave the confines of the germanium. A piece of germanium doped in this manner is called *P-type* germanium, since it lacks electrons and therefore must carry a positive charge.

An analogy which might help clarify the function of the hole is the classic garage full of cars illustration. As shown in figure 1.5-C, the 12-car garage is nearly filled to capacity with 11 automobiles. Naturally, the only empty space is at the rear of the garage. When one drives up to store a car, the attendant moves the front car forward into the space. He then moves the second car up a space. Finally, after moving each car up a space, he makes way for the 12th car. Although the attendant has only moved cars forward, in effect, he has moved the

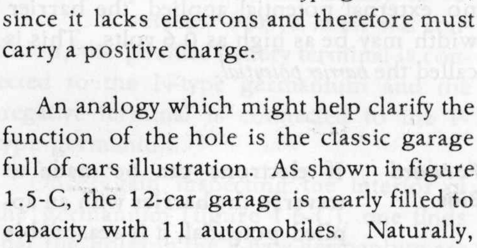
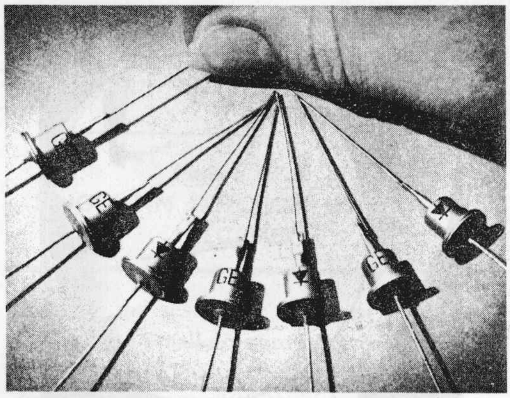


Figure 1.5-C
CLASSIC EXAMPLE SHOWING MOVEMENT OF HOLES



THESE POWER DIODES WILL DO THE SAME JOB AS A 5U4 RECTIFIER
But they will provide more output voltage for an indefinitely long time.
(Courtesy, General Electric Company)

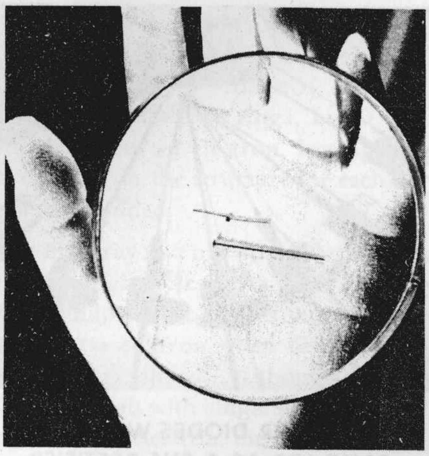
space (the hole) toward the entrance.

When a potential is applied to the P-type germanium, the holes will move in a very orderly fashion and in one direction, which constitutes an electric current. In N-type germanium, the electrons move from the negative to the positive source while in P-type material, the holes traverse from positive to negative. The holes (P) or electrons (N) are termed the *majority carriers* since they make up the majority of moving particles.

1.6 Junctions

The reader with a fair imagination should be able to visualize what happens inside a piece of impurity-doped germanium or silicon, whether type N or type P.

Consider now what happens when blocks of N-type and P-type materials are "sandwiched" together to from a *P-N junction* (figure 1.6-A.) The situation produced by joining of P and N type material is somewhat complex. Remember that when manufactured, P-type material is elec-



PROBABLY THE WORLD'S SMALLEST SEMICONDUCTOR DIODE
The "Tiny Tim." That's not a 16-penny nail; it's a common household pin! (Courtesy, Pacific Semiconductors, Inc.)

trically neutral, as is also the N-type material. Because the atoms in each are sharing electrons or holes, there is no actual surplus of electrons or holes. A surplus or a deficiency of electrons would mean that the germanium (or silicon) was electrically charged. When the two types of germanium are placed together the reader might immediately assume that the excess electrons in the N-type material would join the holes in the P-type material. This is not the case. Although a few *recombinations* do occur, these are caused by thermal agitation. The two sides actually set up a *barrier*, preventing total recombination. If an electron crosses from the N zone to the P zone, both electrically neutral pieces will now take on a charge. The N zone will have lost an electron and the P zone will have gained an electron. The P zone will thus become negative with respect to the N zone. Thus, the negative P zone will now repel the entry of further negative particles. Remember that like poles repel and unlike poles attract. In fact, a barrier is set up between the two junctions, and it takes a potential from a

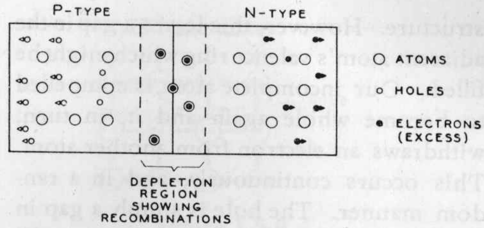


Figure 1.6-A
TWO "BLOCKS" OF GERMANIUM ARE JOINED TO FORM A JUNCTION

battery to force reluctant electrons across the barrier.

The physical width of the barrier is rather indefinite and is usually measured in terms of the voltage necessary to drive an electron across the depletion region. With no external potential applied, the barrier width may be as high as 0.6 volts. This is called the *barrier potential*.

Forward Bias If electrons can be made to traverse the barrier with an applied potential, it is reasonable to assume that the P-N junction will conduct a current.

To obtain *forward bias*, the positive terminal of a battery is connected to the P-type germanium and the negative terminal of the battery is connected to the N-type germanium. If one could examine the inside of these slabs of germanium (figure 1.6-B) it would be seen that the holes are being repelled from the positive terminal and the

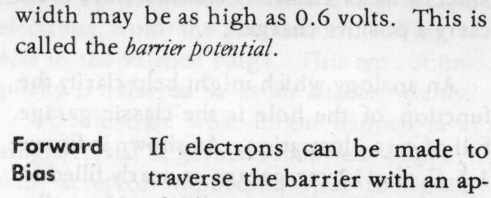


Figure 1.6-B
A GERMANIUM JUNCTION WITH FORWARD-BIAS APPLIED