SEMICONDUCTOR THEORY

The term "semiconductor" denotes a solid material that will not conduct electricity as well as a metallic conductor but will conduct better than an insulator. There are many semiconductor materials. Some are elements and some are compounds. The most common materials are germanium and silicon. Silicon will be discussed here.

In its crystalline form, silicon is a very hard and stable substance (melting point of 1420°C.) yet has no electrostatic forces holding it together. Instead the structure of the silicon atom is tetravalent; in other words, it has four electrons in its outer orbit which are available to combine with the electrons of the other atoms. We picture the atom as:

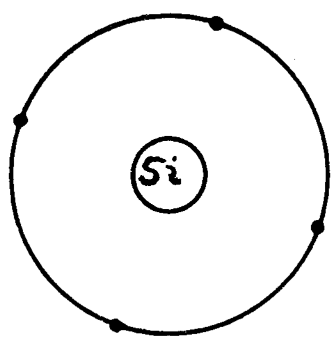


Fig. 1

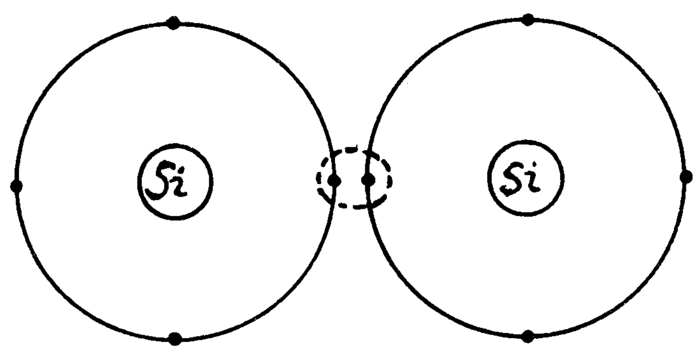


Fig. 2

The crystal will be built up as an array of atoms. Outer electrons will be shared as shown in Fig. 2.

The electron bond in the dashed circle is very strong. Instead of using dots to represent the electrons, usually lines are drawn as shown in Fig. 3.

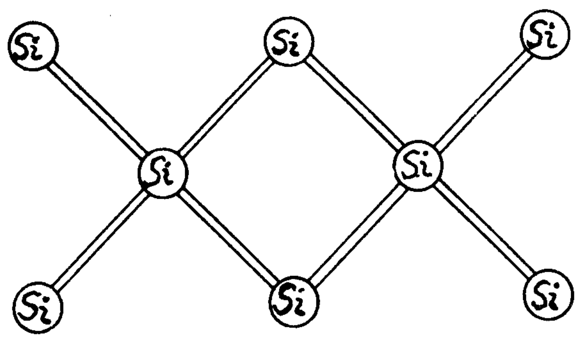


Fig. 3

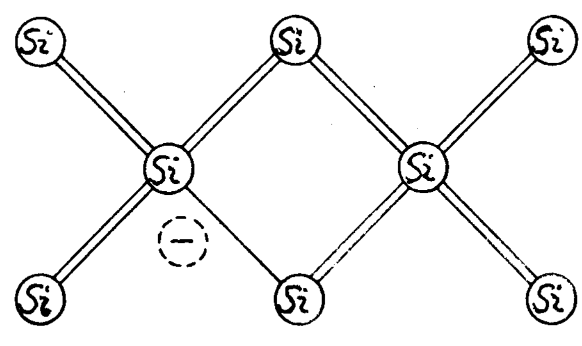


Fig. 4

The electronic structure shown in Fig. 3 is that of an insulator, because there are no free electrons to move if an electric field is applied. If current is to flow, some of the bonds must be broken, or a supply of free electrons must be made available.

In the case of the pure material, free electrons may be obtained by thermal agitation, i.e., by heating the crystal. A broken bond and free electron is shown in Fig. 4.

At the atom where the free electron broke loose, there is now a vacant spot or only one electron left. This is called a hole. The electron is now free to wander in the interstices of the lattice of the crystal. This electron may fall back into the bond or hole, or an adjacent electron may fall into the hole. The movement of the free electron creates a current.

As mentioned above, when the electron is broken away from the atom it leaves a vacant place or a hole. The hole will eventually be filled by another free electron but it is obvious that the electron that fills this hole must have left a hole when it was broken loose somewhere else in the crystal. Thus it can be seen that if the electrons drift toward a positive electrical polarity, the holes can be thought to drift toward the negative polarity. Now we can visualize the total current flow being composed of current flow due to the movement of electrons and current due to the opposite movement of the holes.

From the previous description it can be seen that whenever a bond is broken and an electron is set free there is automatically created a hole, or in other words the electron and hole are formed in pairs. Such a semiconductor has little practical use. The semiconductor material will be useful if the densities of electrons or holes may be varied independently. This may be accomplished by a process known as "doping with impurities".

If an element such as arsenic which is pentavalent (one that has five electrons in the outer orbit) is added to the "intrinsic" or pure silicon, we have an extra electron that is free to move. This may be seen from Fig. 5.

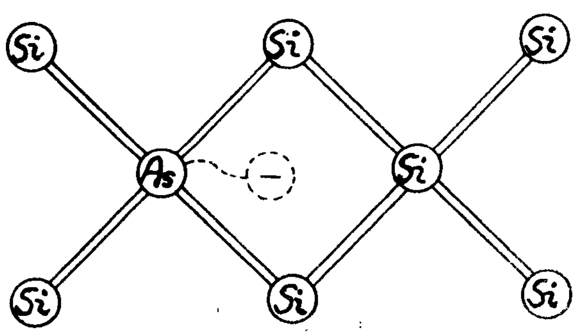


Fig. 5

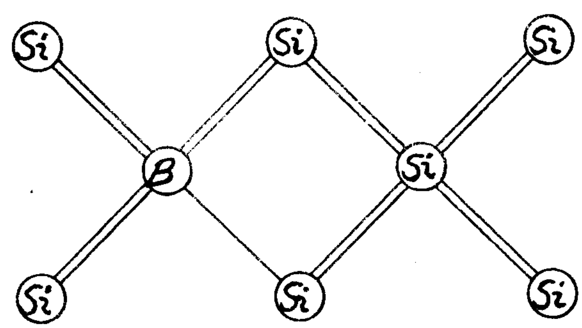


Fig. 6

The picture above shows an arsenic atom surrounded by silicon atoms. All of the bonds are filled and there is one electron left over. When this electron moves from its arsenic atom there is now no hole left to be filled by another electron. Therefore, in this case, only the electrons make up the current. The number of these pentavalent atoms is very small, approximately one atom to one million atoms of silicon. The density of the arsenic impurity may be varied to produce different effects. The pentavalent atoms are called "donors" because of the excess electron and the semiconductor material will be called N-type.

In a similar manner we could have used an element such as boron, the atom of which has only three electrons in the outer orbit. Thus, instead of having an extra electron, we now have a hole. These atoms are known as "acceptor" atoms and the semiconductor material is known as P-type. In material of this type, an adjacent electron can fall into the hole but it will be leaving a hole behind. Thus, it can be seen that the electrons are bonded and the holes are free to move under the influence of an applied electric field. Therefore the current is due to the movement of holes. See Fig. 6 for this type of material.

We now have a semiconductor material which has an excess of electrons and a semiconductor material that has an excess of holes. The simplest configuration that can be made of the two materials is to form a junction between the body of N-type and the body of P-type materials. This is what is known as a p-n junction. See Fig. 7.

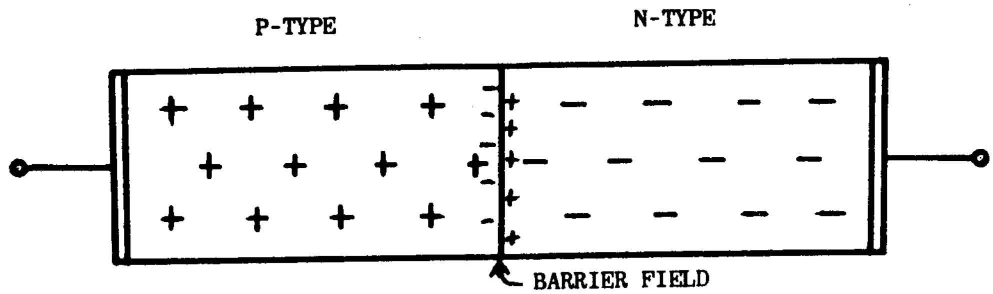


Fig. 7

After a p-n junction is formed, the free electrons and holes in each region remain at the same densities except very near the junction. The holes and electrons in the junction area combine producing ions or electrically charged atoms. These ions produce an electric field which is known as a "barrier field". This barrier field is a very small voltage with the n-material being positive. It is seen that the holes produced in the n-material and the electrons produced in the p-material will flow across the junction. This flow of current is caused by thermal agitation and a contact difference of potential between the two types of semiconductor materials.

If we now apply a positive voltage to the P-material, it is seen that a force is exerted, on the holes and electrons in such a manner so as to oppose the restraining force of the barrier field. This causes the electrons and holes to crowd close to the junction and finally to cross the junction. A large current flows. See Fig. 8A.

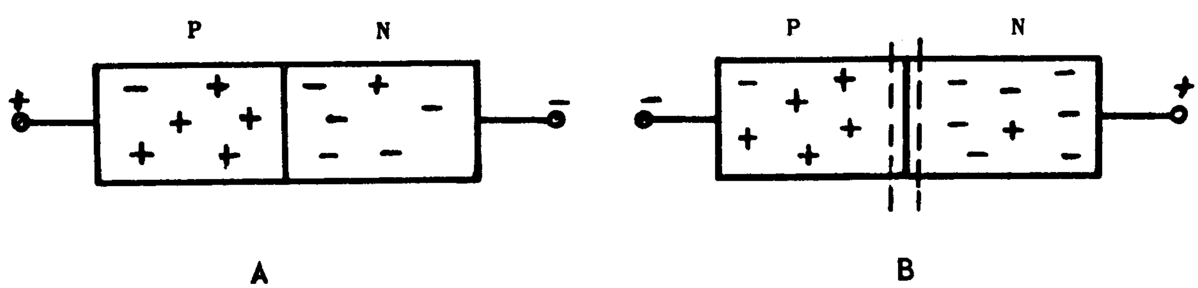


Fig. 8

If we now reverse the applied voltage and apply a negative voltage to the p-material, the barrier field will widen. The electrons and holes will now crowd away from the junction and few will cross the junction. There is almost no current flow. See Fig. 8B. The actual current is not quite zero because some of the crystal bonds near the junction are broken by thermal agitation and a very small current will flow in the reverse direction. The volt-ampere characteristics appear as shown in Fig. 9.

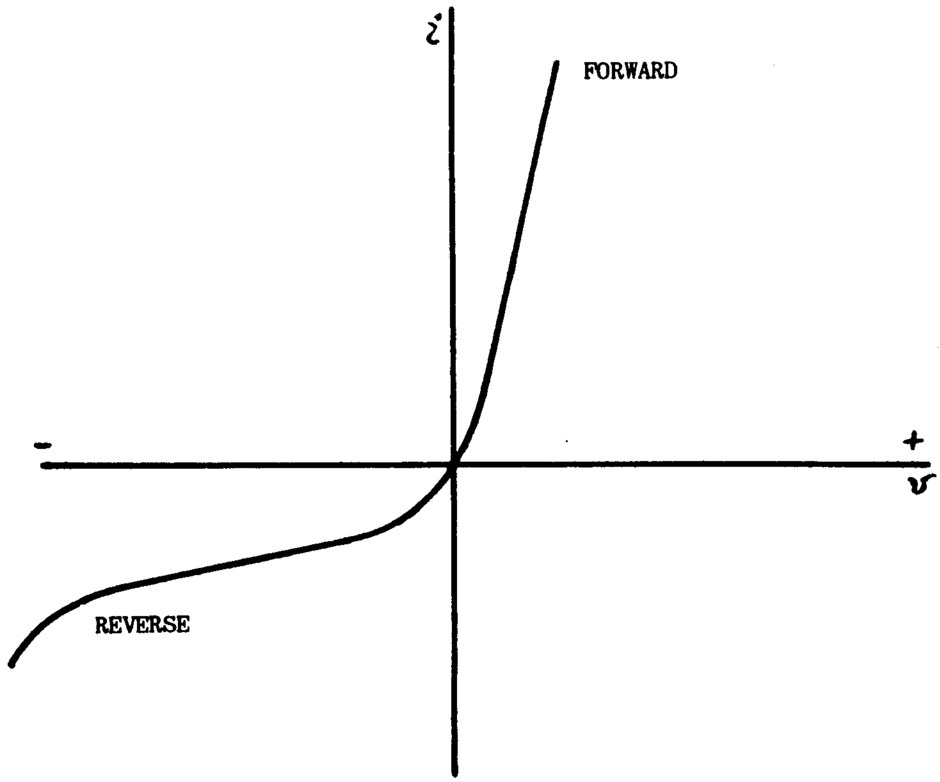


Fig. 9

Some typical values for a silicon rectifier cell would be 100 amps at one volt in the forward direction and 40 milliamperes at 500 volts in the reverse direction. Different sizes of junctions will have different values for the above characteristics. The characteristics will also change with a change in temperature. An increase in temperature will increase the number of electrons and holes set free and thus will decrease the voltage drop across the junction in the forward direction. These same thermally generated pairs add to the reverse leakage current. The highest temperature at which a rectifier may be operated in service is often dictated by the leakage current that may be tolerated. In some cases the circuit dictates what is a tolerable leakage; in other cases the heat dissipated by the reverse leakage in the cell establishes the maximum operating temperature. Silicon cells can be operated as high as 190°C junction temperature but for industrial applications the temperature is kept at 140°C or below.

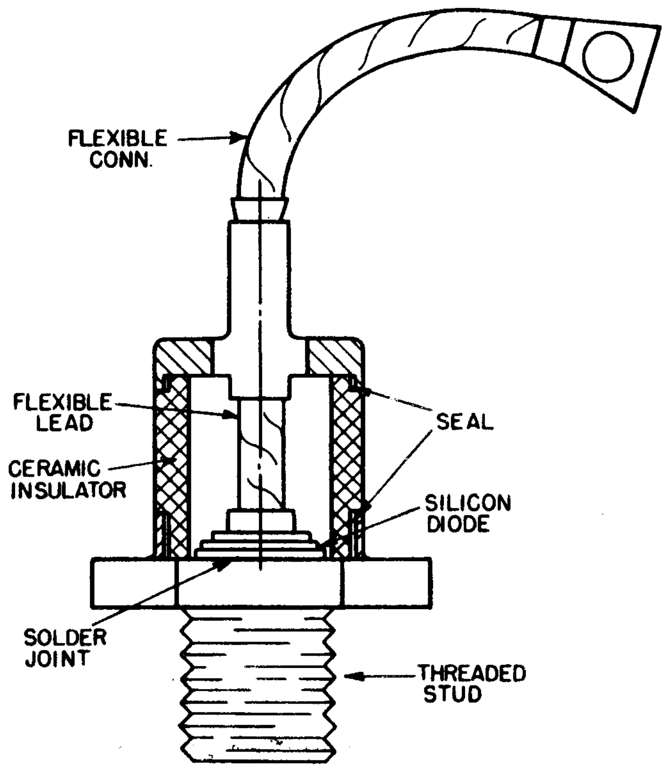
The breakdown voltage in the reverse direction limits the permissible applied voltage in a circuit. Usually for safety and an ability to withstand many uncalculable transient voltages, the silicon cell is applied at about a factor of two below the breakdown voltage.

The p-n junction cell carrying current in the forward direction will generate heat by power dissipation given by:

Power dissipation = forward current x forward voltage drop.

In practice, the cell is usually protected from the corrosive atmosphere by enclosing it in a hermetic seal. See Fig. 10 for a typical cell.

The previous discussion has been concerned with a silicon rectifier cell only. A very simplified version of semiconductor theory has been presented. For a more detailed discussion, a semiconductor theory book should be consulted.



SILICON RECTIFYING CELL

Fig. 10