

Fig. 6 P-Type Semiconductor Material

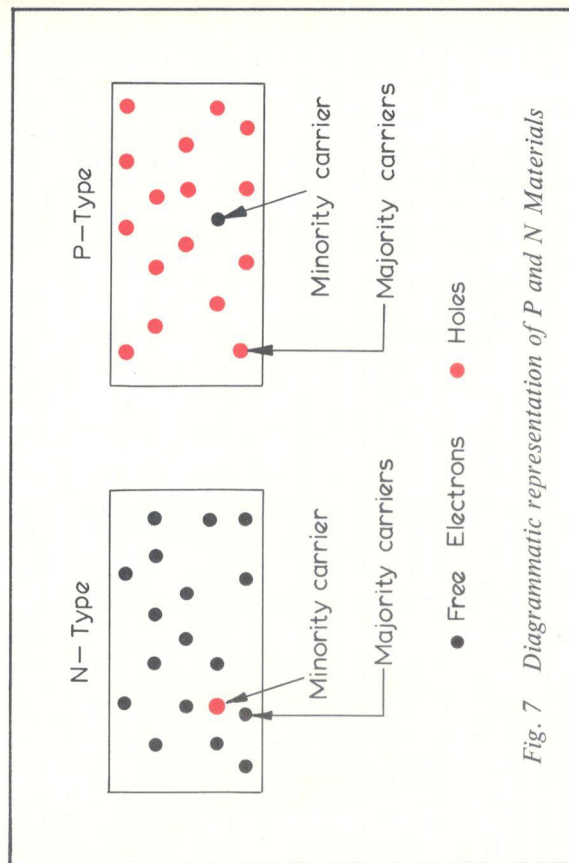


Fig. 7 Diagrammatic representation of P and N Materials

p-type material is electrically neutral. The impurity atoms are called ACCEPTORS because each atom can accept one electron from the lattice.

In future illustrations we shall indicate only the free electrons and holes, as shown in fig. 7. The donor and acceptor atoms are omitted for the sake of clarity. In practice, at room temperatures, semiconductor materials contain a few holes and electrons generated by thermal agitation. In fact thermal generations and recombinations are taking place continuously. Thus p-type material will at all times contain a few free electrons and n-type material will contain a few holes. Of course, there are very few thermally generated electrons and holes and they are therefore called MINORITY CARRIERS. However, most of the carriers in the n- and p-type materials are the electrons and holes introduced deliberately which are called MAJORITY CARRIERS.

Fig. 8 illustrates what happens when a battery is connected to n- and p-type semiconductors. In the n-type, fig. 8a, electrons are attracted to the positive terminal of the battery (because unlike charges attract). The loss of electrons from the left-hand end of the crystal would cause the material to become positively charged. However, this positive charge is cancelled by electrons flowing into the right-hand end from the negative terminal of the battery. This action repeats continuously giving rise to a flow of electrons (i.e. current) through the crystal but the net number of electrons within the crystal at any given instant remains constant.

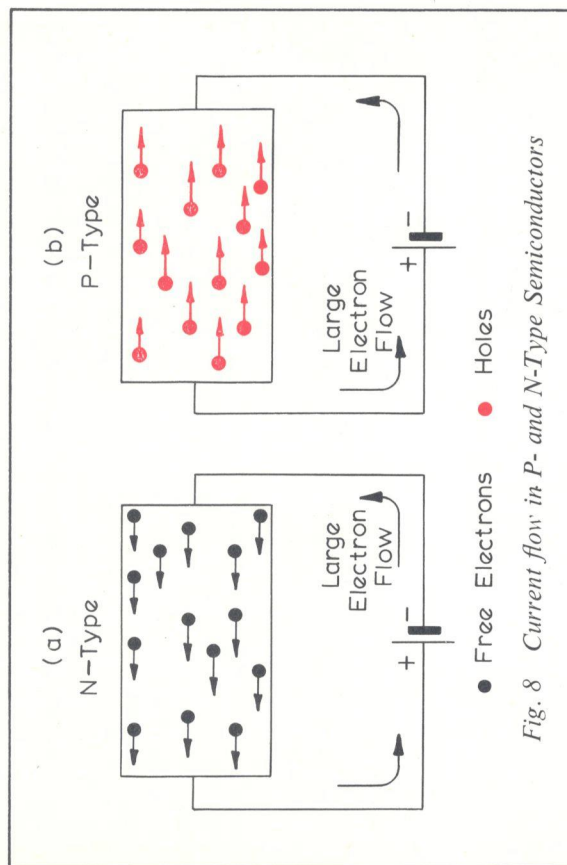


Fig. 8 Current flow in P- and N-Type Semiconductors

In the p-type, fig. 8b, holes reaching the right-hand side are neutralised by a flow of electrons from the negative terminal of the battery. This gain of electrons would cause the crystal to become negatively charged. However, equilibrium is maintained by the necessary number of electrons being ejected from the left-hand end to the positive terminal of the battery. A continuous flow of electrons from the battery results but the number of holes within the crystal at any instant remains constant.

Extraction and Refinement

Germanium is a rare element estimated at seven parts per million in the earth's crust and generally only occurring as a minor impurity in other minerals. Silicon, on the other hand, is extremely common; its oxide silica and silicates comprise 40 per cent of the earth's crust.

Both germanium and silicon form colourless, low boiling point, liquid chlorides, GeCl_4 and SiCl_4 , which can be purified to an extremely high degree by fractionation processes similar to those employed in the petroleum industry. Reduction of these compounds by hydrogen, directly in the case of silicon and via the oxide for germanium, provides the elemental polycrystalline materials necessary for semiconductor applications. Nowadays the materials produced in this way require no further purification.

In early years, in order to obtain really pure semiconductor materials, it was necessary to employ a further process known as 'zone refining'. This method is now only of minor importance but is described here for completeness. By eddy current heating it is possible to pass a molten zone along a rod of germanium or silicon. When such a zone passes through the material nearly all impurities present are rejected at the solidifying face of the zone and hence are efficiently swept along in the liquid towards one end of the rod. Afterwards this end can be cut off. In practice several zones are successively passed through a rod reducing the impurity levels to under one part in 10^{10} . Germanium is less chemically reactive than silicon so that this process can be carried out with rectangular section ingots contained in horizontal graphite boats, whereas for silicon a free cylindrical rod is supported at each end vertically and the molten zone remains in position purely by its liquid surface tension forces.

Crystal Growth and Mechanical Processes

For the manufacture of semiconductor devices it is necessary to convert the refined polycrystalline material into single crystal; at the same time intro-

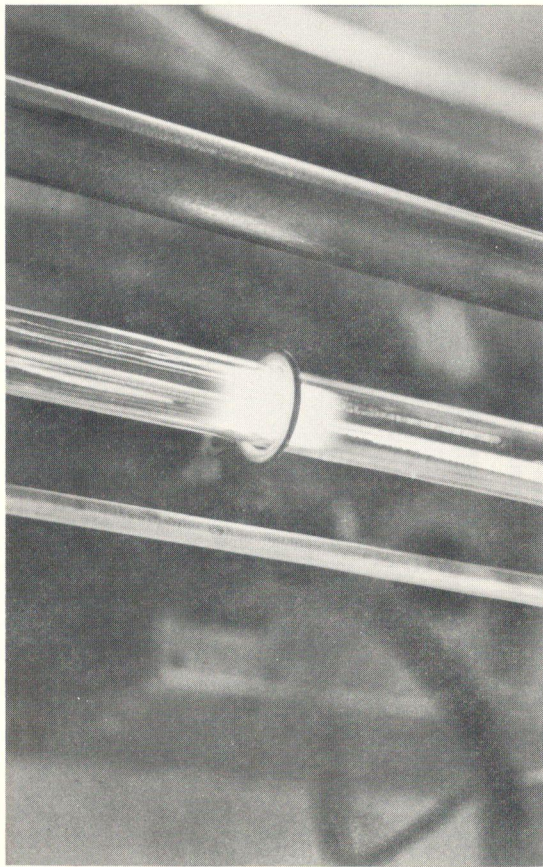


Fig. 9 Single crystal forming by the floating zone method

ducing controlled amounts of specific impurities to obtain the desired electrical resistivity and type. The dopants commonly used are phosphorus or antimony for n-type and boron for p-type. These are added either in the form of alloys with germanium and silicon or elementally for highly doped materials.

Although single crystals can be formed by a finely controlled floating zone method, fig. 9, crystal pulling offers certain advantages and is the more widely used method.

In Czochralski crystal pulling, fig. 10, blocks of the refined material together with a small measured amount of dopant are melted together in a crucible in an inert gas atmosphere. For germanium (m.p. 936°C) a graphite crucible is used whilst for silicon (m.p. 1412°C) it is made of silica. The temperature is allowed to stabilise at just above the melting point value when a thin rod of single crystal material—the 'seed'—is lowered into contact with the melt. Then by variations of the temperature, and the rates of rotation and withdrawal of the seed, the molten material is gradually frozen on to it as a single crystal of controlled diameter and resistivity. Eventually the crucible is left almost empty. Such crystals can be 50 to 75mm in diameter and weigh up to 5kgm.

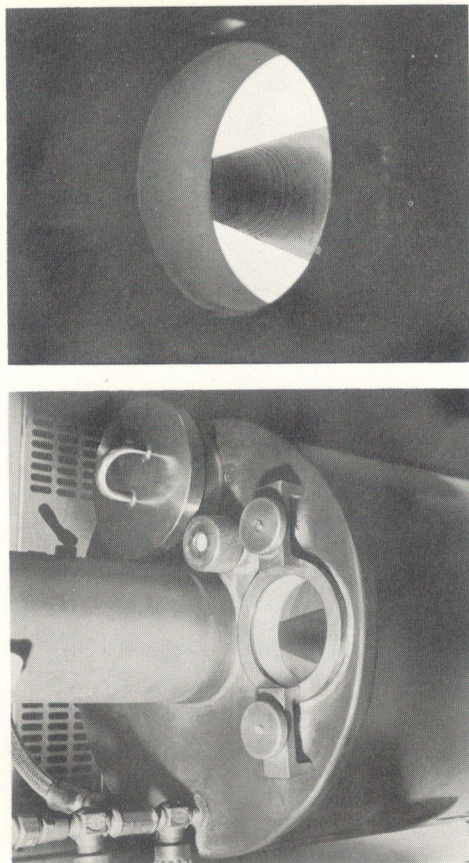


Fig. 10 Czochralski crystal puller and close-up showing the start of the crystal pull

After the single crystal has been grown it is carefully tested to ensure that it is of the desired resistivity and type and of acceptable crystallographic perfection. It then goes through a series of mechanical operations leading to various end products according to the device requirements. The ingots are first cut into slices of controlled thickness using high speed diamond edged saws, with the surfaces set to chosen crystallographic directions. The slices may next be machine lapped flat and parallel to extremely close thickness tolerances and then ultrasonically trepanned. On the other hand, they may be sawn into circular or square 'dice' of various sizes for the manufacture of diodes or transistors such as the OC71 (Ge) or OC200 (Si). Alternatively the cut slices may be polished parallel to optical standards for the planar or epitaxial techniques described later in this book. Only a brief outline of these mechanical operations has been given but it should be recognised that a high degree of expertise is essential in this area.

Epitaxy

The term 'epitaxial growth' is applied to the deposition of a solid layer of material of high crystal perfection on an underlying substrate. The substrate is not necessarily of the same chemical composition as the epitaxial layer. The layer has a definite lattice orientation to the substrate.

When a gaseous mixture of hydrogen and silicon tetrachloride is passed over a substrate comprising a clean polished slice of single crystal silicon held at a temperature of 1000 to 1200°C, a reaction occurs and a silicon layer is deposited on the substrate. If the process has been properly controlled this layer is a high quality single crystal of the same orientation as the substrate. By adding suitable dopants to the gas mixture (such as phosphine PH_3 or diborane B_2H_6) the electrical resistivity and type of the layer are specified.

Furthermore, by the careful addition of small amounts of oxygen or ammonia into the gas stream, silicon oxide or silicon nitride insulating layers can be formed either on the substrate or over the epitaxial layer.

Epitaxial deposition is a flexible process with wide application in planar and integrated circuit processes at various stages of manufacture.

SECTION 2 — THE SEMICONDUCTOR DIODE

Introduction

Basically the semiconductor diode consists of a piece of n-type and a piece of p-type semiconductor joined together (fig. 11). The two electrodes are the anode (p-type) and the cathode (n-type). The actual construction is dealt with in section 4.

Naturally, as soon as the junction is formed there will be a drift of carriers across it. Holes move into the n-type and electrons move into the p-type. At first sight it might be expected that all the electrons in the n-type would move into the p-type and that all the holes would move into the n-type resulting in a total disappearance of all carriers. However, once a few electrons have entered the p-type they make it negatively charged (both regions were initially neutral). Similarly the gain of holes by the n-type makes it positively charged, fig. 12. Since like charges repel, the negative charge opposes the further flow of electrons and the positive charge opposes the further flow of holes. The situation then is just as if there were a small battery across the junction. For simplicity, in fig. 12, the region near the junction is shown devoid of carriers. This carrier free area is called the **BARRIER** or **DEPLETION** region.

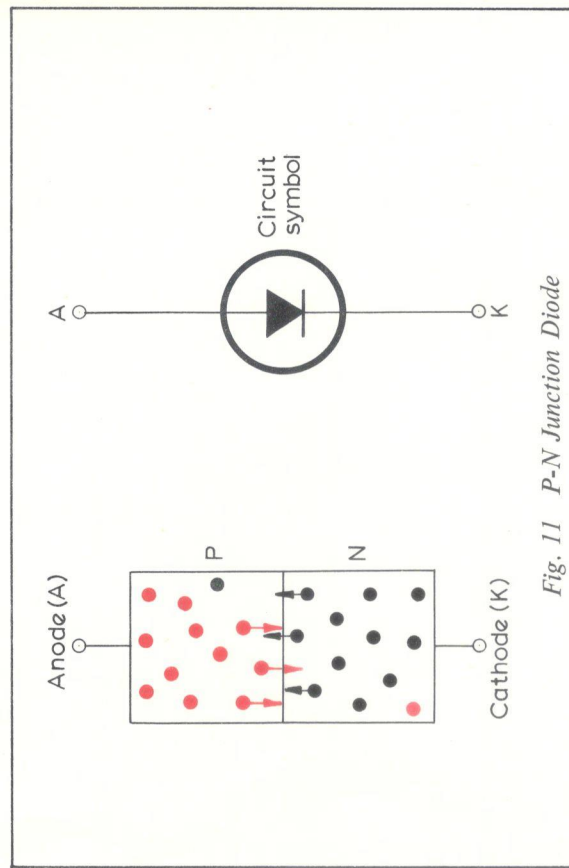


Fig. 11 P-N Junction Diode

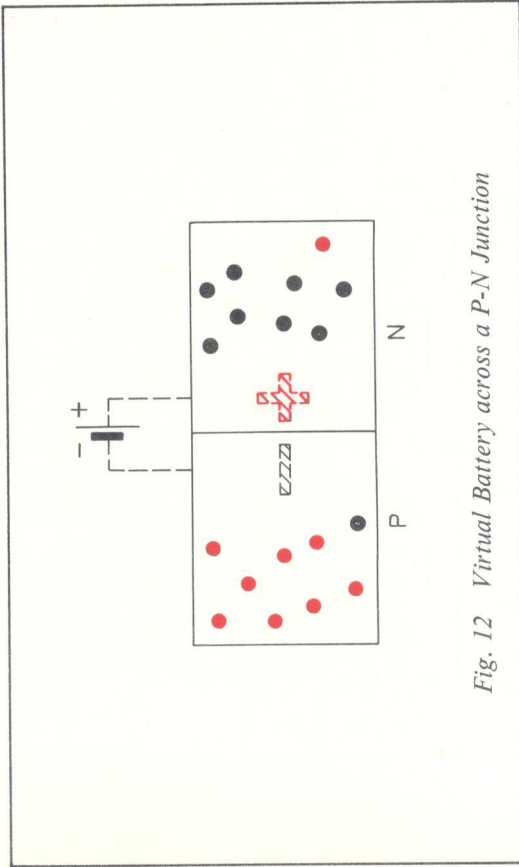


Fig. 12 Virtual Battery across a P-N Junction

Reverse Bias

If a real battery is now connected the same way round as the virtual battery, fig. 13, the barrier region is broadened and no majorities can cross the junction. Only the occasional minority carriers generated thermally cross the junction and a very small flow of current, called the **LEAKAGE CURRENT** results. The diode is now said to be **REVERSE BIASED**. The leakage current in germanium diodes is far greater than that in silicon diodes.

Forward Bias

If on the other hand the real battery which is larger than the virtual battery is connected in opposition to it, fig. 14, a considerable flow of current results. Holes attracted by the negative terminal of the battery drift to the right towards the junction; on reaching it they are cancelled by electrons from the n-type; this loss of electrons from the n-type is compensated for by more electrons being simultaneously injected by the negative terminal of the battery. As holes from the p-type are cancelled at the junction, electrons are simultaneously released from its left-hand to the positive terminal of the battery. The small leakage current due to minorities adds to the main majority flow. A large current flows and the diode is now said to be **FORWARD BIASED**.

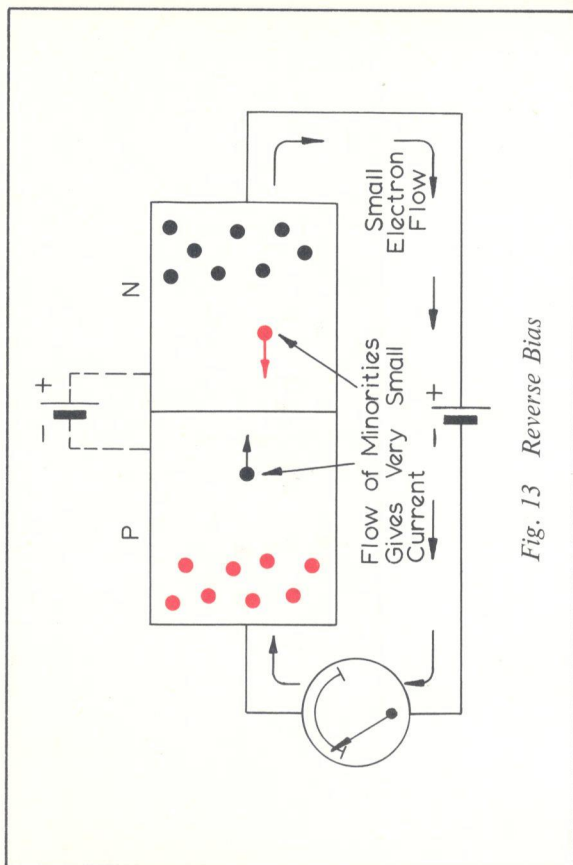


Fig. 13 Reverse Bias

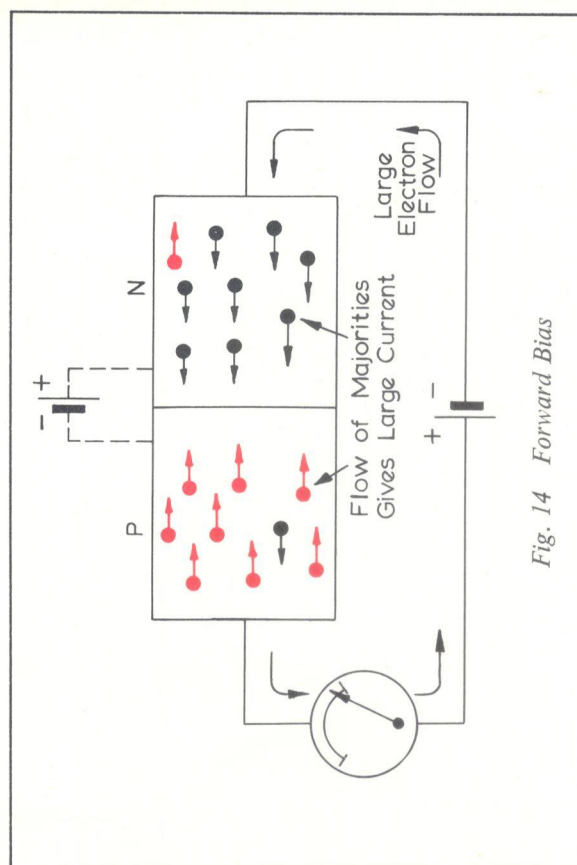


Fig. 14 Forward Bias

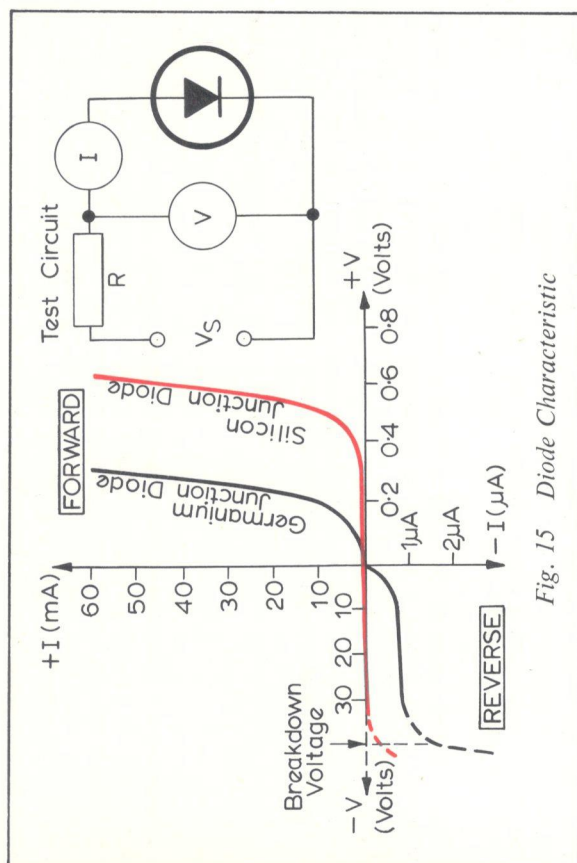


Fig. 15 Diode Characteristic

The Diode Characteristic

Fig. 15 illustrates the shape of the characteristic. The virtual battery across the junction is small and so only a fraction of a volt need be applied in the forward direction to start a current. This 'turn-on' voltage is of the order of 200mV for germanium diodes and 600mV for silicon diodes. Once this voltage has been reached an extremely small change in voltage results in large changes in current. This situation is illustrated by the fact that the curves become very steep, they are in fact exponentials. The forward current could quickly become large enough to damage the device and hence, in the test circuit, a limiting resistor R is added.

In the reverse direction, however, so little current flows that it is necessary to inflate the $-I$ scale in order to see the current at all. The fact that the leakage current for silicon diodes is much less than for germanium diodes is clearly illustrated by the reverse characteristic. There comes a point, however, when 'breakdown' occurs and a considerable current flows. At low voltages breakdown is caused by electrons breaking away from their covalent bonds (the ZENER effect). At higher voltages it is caused by the minority electrons gaining sufficient velocity to dislodge other electrons from their atoms. These new electrons are then themselves accelerated and, in turn, can produce more electrons. There is therefore a sudden build-up of