Unit 23 Diode structure and operation

- A diode is formed from a single crystal. The doping changes from p-type to n-type within the crystal.
- Current flows through the forward biased diode when:
  - the p-type anode is at a positive voltage
  - the n-type cathode is at a negative voltage.
- Conventional current flows in the direction of the arrow of the diode symbol.
- The current-voltage characteristic for the diode is determined by the positions of the energy levels and the occupancy of the energy levels of the diode material.
- The depletion layer in a reverse biased diode is the region around the junction from which mobile charge carriers have been removed.
- The depletion layer forms a capacitance whose thickness depends on the reverse bias voltage.
- Ohmic contacts are made between the silicon crystal and the connecting wires.
- The bulk resistance associated with the silicon crystal and connections is of the order of $1\,\Omega$ and limits the maximum forward current through the diode.

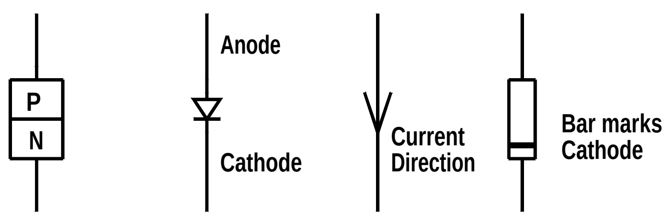

Figure 23.1: Junction diode.

A piece of p-type or n-type doped semiconductor, electrically speaking, is simply a resistor without any special properties. The valuable properties of semiconductors only appear when there is a change of doping or junction between two doped regions within a single piece of crystalline semiconductor.

We can visualize a bar of semiconductor which has been fabricated with p-type material at the top and n-type material at the bottom as shown in Figure 23.2 (a). Typical actual dimensions would be a cross section of 1 mm^2

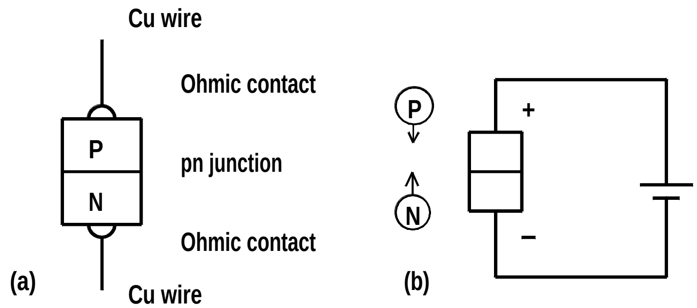

Figure 23.2: Junction diode construction and operation.

with a height of 20 microns and a junction thickness of 1 micron. The diagram in Figure 23.2 (a) has been magnified in height. Ohmic contacts are made to the top and bottom of the semiconductor crystal by bonding on contacts using metals such as gold or aluminium.

Suppose that the diode is put into a circuit as shown in Figure 23.2 (b), with a positive voltage applied to the p-type anode and a negative voltage applied to the n-type cathode. Looking in detail at the processes within the semiconductor, we can see that the p-type holes in the p-type anode region are pushed by the applied electric field down towards the junction and cross the junction into the n-type material to become minority carriers within the cathode. These holes then recombine with an n-type electron or else move to the cathode ohmic contact where they are neutralized by an incoming electron. In either case the result is simply that there is a transfer of positive charge from the anode to the cathode, in other words an electric current flows.

Within the cathode, the n-type carriers are attracted to the positive voltage on the anode, cross the junction and again contribute to the flow of charge around the circuit. So when the p-type anode is positively biased and the n-type cathode is negatively biased, current flows around the circuit. The diode is then said to be forward biased.

Now consider the case shown in Figure 23.3 where the bias voltage is reversed, with the anode negative and the cathode positive. In this case the

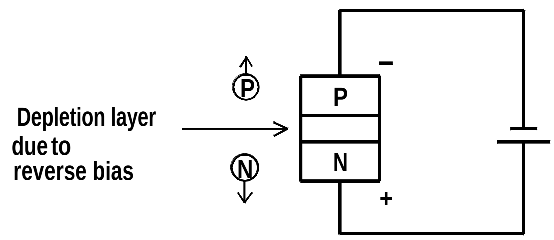

Figure 23.3: Junction diode in reverse bias.

p-type carriers in the anode are attracted away from the junction by the negative voltage on the anode. Similarly the n-type carriers in the cathode region are also attracted away from the junction by the positive voltage applied to the cathode terminal. The net effect is that the majority carriers in each region are pulled away from the junction to leave a region depleted of mobile charges called the depletion layer. There will therefore be no significant current through the diode when a reverse bias is applied. We then have the result that a diode is a device which passes electrical current in one direction but blocks the flow of current in the opposite direction.

However, even when the diode is reverse biased, a very small current flows. This reverse current arises because within the p-type anode region there are some minority carriers whose concentration is given by the semiconductor equation, $n \times p = n_i^2$. Similarly, within the n-type cathode region there are also some p-type carriers present. The reverse bias on the diode is only a reverse bias for majority carriers. For minority carriers it is a forward bias. So we get a very small constant current in a reverse biased diode which depends on the temperature and on the doping concentrations in anode and cathode regions which control the minority carrier concentrations. The reverse current is, however, independent of the reverse bias voltage. At room temperature the reverse current is typically 10^{-10} A for a silicon diode and 10^{-6} A for a germanium diode.

Silicon and germanium have different band gap energies and therefore different intrinsic carrier concentrations, n_i, so for comparable doping levels it is reasonable to expect that the minority carrier concentrations are different and therefore the reverse bias currents are also different.

One fabrication problem relates to making a connection to the semiconductor material. If a metal, which is essentially an n-type conductor, is connected to a p-type semiconductor then, in principle, a pn junction is formed which would have some rectifying properties. This problem is avoided and a fully ohmic or nonrectifying contact is formed when a metal with a work function greater than that of the p-type semiconductor work function is used to make the contact. An ohmic contact is made to an n-type semiconductor by using a metal having a work function less than that of the semiconductor work function. Choice of a different metal, with a different work function, for the contact metal can lead to the formation of a diode called a Schottky metal semiconductor junction diode.

(The work function of a metal or semiconductor is the energy difference between an electron within the crystal having an energy at the Fermi energy level and an electron moving freely outside the crystal. Typical work functions are of the order of a few electron volts.)

A historical example of such a Schottky diode is the cat's whisker diode which was used as the rectifier in the very first radio receivers and which consisted of a metal point poked at a piece of galena crystal (lead sulphide ore) until a rectifying diode was formed. A steady hand was required to maintain the rectifying contact for the duration of the radio program!

23.1 Problems

23.1 The capacitance of a parallel plate capacitor is given by $C = \frac{\kappa \epsilon_0 A}{d}$. The area A of a particular diode junction is $0.5\,\mathrm{mm}^2$. The capacity of the reverse biased diode is measured using a Boonton capacitance meter and is found to be 40 pF. Calculate the thickness of the depletion layer, d. The dielectric constant, κ, of silicon can be taken to be 5.0. If the reverse bias is increased, will the junction capacitance increase or decrease? $\epsilon_0 = 8.854 \times 10^{-12}\,\mathrm{F\,m^{-1}}$.

23.2 A varactor diode or varicap is a diode designed to have a large depletion layer capacitance when used in reverse bias. One formula for the capacitance of a varactor diode as a function of the reverse bias voltage is:

$$C(V) = \frac{C_0}{\left(1 + \frac{V}{\phi}\right)^{0.44}}$$

where $C_0 = 80\,\mathrm{pF}$ and $\phi = 0.6\,\mathrm{V}$.

If such a diode is used, connected in parallel with an inductance of $12\,\mu\mathrm{H}$ in the tuning circuit of a radio, plot a graph of the resonant frequency as a function of the reverse bias voltage for voltages from 0.5 V to 5.0 V.

23.3 If the temperature increases, will the reverse current through a diode increase or decrease?

23.4 How do you identify which end of a diode is the cathode end?

23.5 In each of the circuits shown in Figures 23.4 (a) to (e), indicate which diodes are forward biased and which are reverse biased. Also indicate whether you expect current to flow or not to flow. Why are resistors included in the circuits?

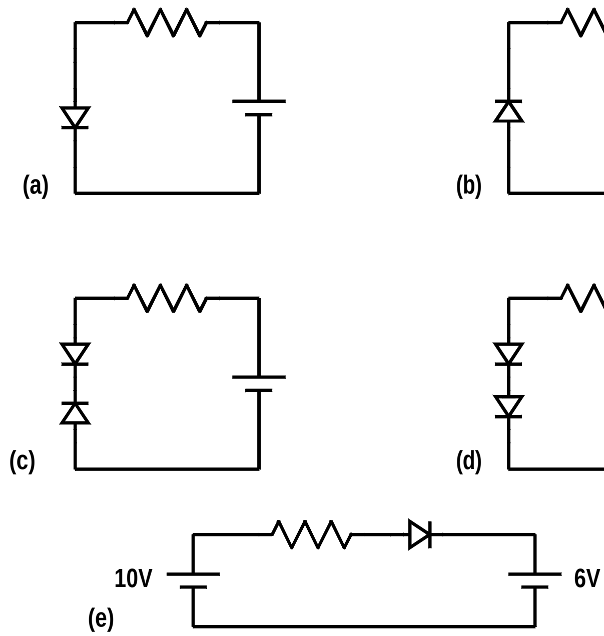

Figure 23.4: Problem 23.4.

23.6 If the resistivity of a semiconductor sample is inversely proportional to the number of mobile charge carriers present, calculate the change in the resistivity of a silicon sample when the n-type doping is increased from the intrinsic concentration to three times the intrinsic concentration.