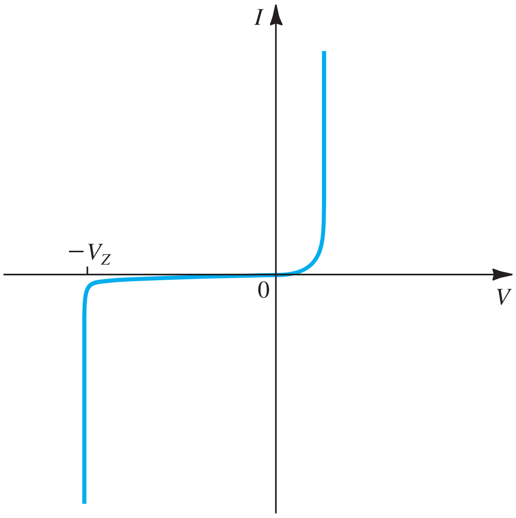

Figure 3.14 The I–V characteristic of the *pn* junction showing the rapid increase in reverse current in the breakdown region.

remains very close to the value V_Z. The phenomenon that occurs at $V = V_Z$ is known as **junction breakdown**. It is not a destructive phenomenon. That is, the *pn* junction can be repeatedly operated in the breakdown region without a permanent effect on its characteristics. This, however, is predicated on the assumption that the magnitude of the reverse-breakdown current is limited by the external circuit to a "safe" value. The "safe" value is one that results in the limitation of the power dissipated in the junction to a safe, allowable level.

There are two possible mechanisms for *pn* junction breakdown: the **zener effect**[7] and the **avalanche effect**. If a *pn* junction breaks down with a breakdown voltage $V_Z < 5$ V, the breakdown mechanism is usually the zener effect. Avalanche breakdown occurs when V_Z is greater than approximately 7 V. For junctions that break down between 5 V and 7 V, the breakdown mechanism can be either the zener or the avalanche effect or a combination of the two.

Zener breakdown occurs when the electric field in the depletion layer increases to the point of breaking covalent bonds and generating electron–hole pairs. The electrons generated in this way will be swept by the electric field into the *n* side and the holes into the *p* side. Thus these electrons and holes constitute a reverse current across the junction. Once the zener effect starts, a large number of carriers can be generated, with a negligible increase in the junction voltage. Thus the reverse current in the breakdown region will be large and its value must be determined by the external circuit, while the reverse voltage appearing between the diode terminals will remain close to the specified breakdown voltage V_Z.

The other breakdown mechanism, avalanche breakdown, occurs when the minority carriers that cross the depletion region under the influence of the electric field gain sufficient kinetic energy to be able to break covalent bonds in atoms with which they collide. The carriers liberated by this process may have sufficiently high energy to be able to cause other carriers to be liberated in another ionizing collision. This process keeps repeating in the fashion of an avalanche, with the result that many carriers are created that are able to support any value of

[7]Named after an early worker in the area. Note that the subscript Z in V_Z denotes *zener*. We will use V_Z to denote the breakdown voltage whether the breakdown mechanism is the zener effect or the avalanche effect.

reverse current, as determined by the external circuit, with a negligible change in the voltage drop across the junction.

As will be seen in Chapter 4, some *pn* junction diodes are fabricated to operate specifically in the breakdown region, where use is made of the nearly constant voltage V_Z.

3.6 Capacitive Effects in the *pn* Junction

There are two charge-storage mechanisms in the *pn* junction. One is associated with the charge stored in the depletion region, and the other is associated with the minority-carrier charge stored in the *n* and *p* materials as a result of the concentration profiles established by carrier injection. While the first is easier to see when the *pn* junction is reverse biased, the second is in effect only when the junction is forward biased.

3.6.1 Depletion or Junction Capacitance

When a *pn* junction is reverse biased with a voltage V_R, the charge stored on either side of the depletion region is given by Eq. (3.32),

$$Q_J = A\sqrt{2\epsilon_s q \frac{N_A N_D}{N_A + N_D}(V_0 + V_R)}$$

Thus, for a given *pn* junction,

$$Q_J = \alpha\sqrt{V_0 + V_R} \tag{3.42}$$

where α is given by

$$\alpha = A\sqrt{2\epsilon_s q \frac{N_A N_D}{N_A + N_D}} \tag{3.43}$$

Thus Q_J is nonlinearly related to V_R, as shown in Fig. 3.15. This nonlinear relationship makes it difficult to define a capacitance that accounts for the need to change Q_J whenever V_R is

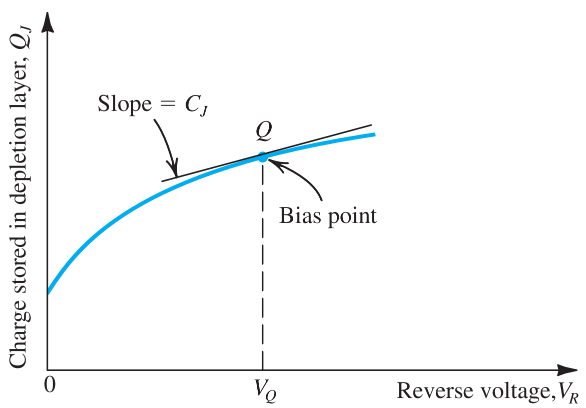

Figure 3.15 The charge stored on either side of the depletion layer as a function of the reverse voltage V_R.

changed. We can, however, assume that the junction is operating at a point such as Q, as indicated in Fig. 3.15, and define a capacitance C_j that relates the change in the charge Q_J to a change in the voltage V_R,

$$C_j = \left.\frac{dQ_J}{dV_R}\right|_{V_R=V_Q} \tag{3.44}$$

This incremental-capacitance approach turns out to be quite useful in electronic circuit design, as we shall see throughout this book.

Using Eq. (3.44) together with Eq. (3.42) yields

$$C_j = \frac{\alpha}{2\sqrt{V_0+V_R}} \tag{3.45}$$

The value of C_j at zero reverse bias can be obtained from Eq. (3.45) as

$$C_{j0} = \frac{\alpha}{2\sqrt{V_0}} \tag{3.46}$$

which enables us to express C_j as

$$C_j = \frac{C_{j0}}{\sqrt{1+\dfrac{V_R}{V_0}}} \tag{3.47}$$

where C_{j0} is given by Eq. (3.46) or alternatively if we substitute for α from Eq. (3.43) by

$$C_{j0} = A\sqrt{\left(\frac{\epsilon_s q}{2}\right)\left(\frac{N_A N_D}{N_A+N_D}\right)\left(\frac{1}{V_0}\right)} \tag{3.48}$$

Before leaving the subject of depletion-region or junction capacitance we point out that in the *pn* junction we have been studying, the doping concentration is made to change abruptly at the junction boundary. Such a junction is known as an **abrupt junction**. There is another type of *pn* junction in which the carrier concentration is made to change gradually from one side of the junction to the other. To allow for such a **graded junction**, the formula for the junction capacitance (Eq. 3.47) can be written in the more general form

$$C_j = \frac{C_{j0}}{\left(1+\dfrac{V_R}{V_0}\right)^m} \tag{3.49}$$

where m is a constant called the **grading coefficient**, whose value ranges from 1/3 to 1/2 depending on the manner in which the concentration changes from the p to the n side.