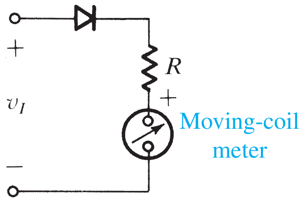

Figure E4.5

Find the value of R that results in the meter indicating a full-scale reading when the input sine-wave voltage v_I is 20 V peak-to-peak. (*Hint:* The average value of half-sine waves is V_p/π.)

Ans. 3.133 kΩ

4.2 Terminal Characteristics of Junction Diodes

The most common implementation of the diode utilizes a *pn* junction. We have studied the physics of the *pn* junction and derived its i–v characteristic in Chapter 3. That the *pn* junction is used to implement the diode function should come as no surprise: the *pn* junction can conduct substantial current in the forward direction and almost no current in the reverse direction. In this section we study the i–v characteristic of the *pn* junction diode in detail in order to prepare ourselves for diode circuit applications.

Figure 4.7 shows the i–v characteristic of a silicon junction diode. The same characteristic is shown in Fig. 4.8 with some scales expanded and others compressed to reveal details. Note that the scale changes have resulted in the apparent discontinuity at the origin.

As indicated, the characteristic curve consists of three distinct regions:

1. The forward-bias region, determined by $v > 0$
2. The reverse-bias region, determined by $v < 0$
3. The breakdown region, determined by $v < -V_{ZK}$

These three regions of operation are described in the following sections.

4.2.1 The Forward-Bias Region

The forward-bias—or simply forward—region of operation is entered when the terminal voltage v is positive. In the forward region the i–v relationship is closely approximated by

$$i = I_S\left(e^{v/V_T} - 1\right) \tag{4.1}$$

In this equation[1] I_S is a constant for a given diode at a given temperature. A formula for I_S in terms of the diode's physical parameters and temperature was given in Eq. (3.41). The current

[1]Equation (4.1), the diode equation, is sometimes written to include a constant n in the exponential,

$$i = I_S(e^{v/nV_T} - 1)$$

with n having a value between 1 and 2, depending on the material and the physical structure of the diode. Diodes using the standard integrated-circuit fabrication process exhibit $n = 1$ when operated under normal conditions. For simplicity, we shall use $n = 1$ throughout this book, unless otherwise specified.

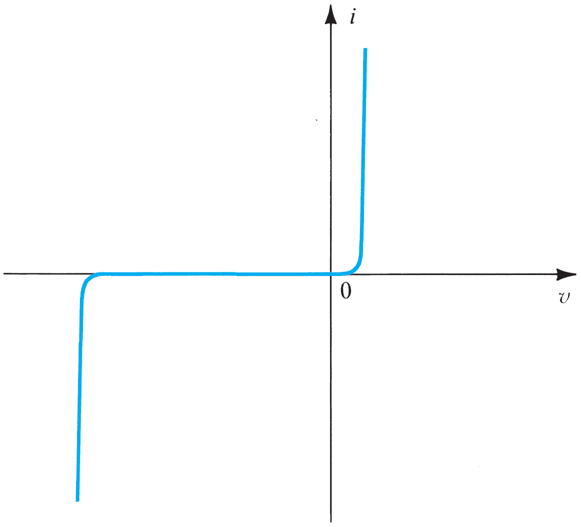

Figure 4.7 The i–v characteristic of a silicon junction diode.

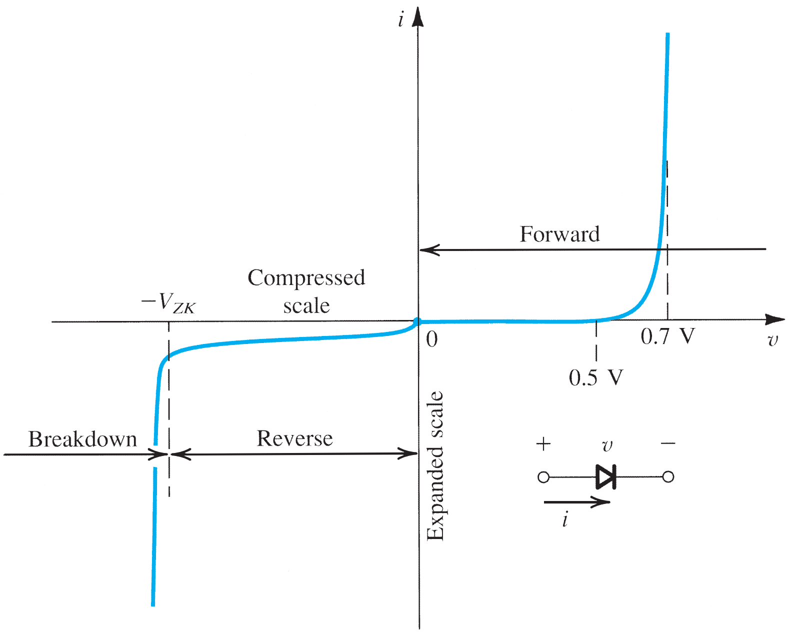

Figure 4.8 The diode i–v relationship with some scales expanded and others compressed in order to reveal details.

I_S is usually called the **saturation current** (for reasons that will become apparent shortly). Another name for I_S, and one that we will occasionally use, is the **scale current**. This name arises from the fact that I_S is directly proportional to the cross-sectional area of the diode. Thus doubling of the junction area results in a diode with double the value of I_S and, as the diode equation indicates, double the value of current i for a given forward voltage v. For "small-signal" diodes, which are small-size diodes intended for low-power applications, I_S is on the order of 10^{-15} A. The value of I_S is, however, a very strong function of temperature. As a rule of thumb, I_S doubles in value for every 5°C rise in temperature.

The voltage V_T in Eq. (4.1) is a constant called the **thermal voltage** and is given by

$$V_T = \frac{kT}{q} \tag{4.2}$$

where

k = Boltzmann's constant = 8.62×10^{-5} eV/K = 1.38×10^{-23} joules/kelvin
T = the absolute temperature in kelvins = 273 + temperature in °C
q = the magnitude of electronic charge = 1.60×10^{-19} coulomb

Substituting $k = 8.62 \times 10^{-5}$ eV/K into Eq. (4.2) gives

$$V_T = 0.0862T, \text{ mV} \tag{4.2a}$$

Thus, at room temperature (20°C) the value of V_T is 25.3 mV. In rapid approximate circuit analysis we shall use $V_T \simeq 25$ mV at room temperature.[2]

For appreciable current i in the forward direction, specifically for $i \gg I_S$, Eq. (4.1) can be approximated by the exponential relationship

$$i \simeq I_S e^{v/V_T} \tag{4.3}$$

This relationship can be expressed alternatively in the logarithmic form

$$v = V_T \ln \frac{i}{I_S} \tag{4.4}$$

where ln denotes the natural (base e) logarithm.

The exponential relationship of the current i to the voltage v holds over many decades of current (a span of as many as seven decades—i.e., a factor of 10^7—can be found). This is quite a remarkable property of junction diodes, one that is also found in bipolar junction transistors and that has been exploited in many interesting applications.

Let us consider the forward i–v relationship in Eq. (4.3) and evaluate the current I_1 corresponding to a diode voltage V_1:

$$I_1 = I_S e^{V_1/V_T}$$

Similarly, if the voltage is V_2, the diode current I_2 will be

$$I_2 = I_S e^{V_2/V_T}$$

[2]A slightly higher ambient temperature (25°C or so) is usually assumed for electronic equipment operating inside a cabinet. At this temperature, $V_T \simeq 25.8$ mV. Nevertheless, for the sake of simplicity and to promote rapid circuit analysis, we shall use the more arithmetically convenient value of $V_T \simeq 25$ mV throughout this book.