

## The Diode

### Basic Operation

The diode is fabricated of a semiconductor material, usually silicon, which is doped with two impurities. One side is doped with a donor or n-type impurity which releases electrons into the semiconductor lattice. These electrons are not bound and are free to move about. Because there is no net charge in the donor impurity, the n-type semiconductor is electrically neutral. The other side is doped with an acceptor or p-type impurity which imparts free holes into the lattice. A hole is the absence of an electron which acts as a positive charge. The p-type semiconductor is also electrically neutral because the acceptor material adds no net charge.

Figure 1(a) illustrates the cross section of the diode. The junction is the dividing line between the n-type and p-type sides. Thermal energy causes the electrons and holes to move randomly. Electrons diffuse across the junction into the p-type side and holes diffuse across the junction into the n-type side. This causes a net positive charge to develop in the n-type side and a net negative charge to develop in the p-type side. These charges set up an electric field across the junction which is directed from the n-type side to the p-type side. The electric field opposes further diffusion of the electrons and holes. The region in which the electric field exists is called the depletion region. There are no free electrons or holes in this region because the electric field sweeps them out.

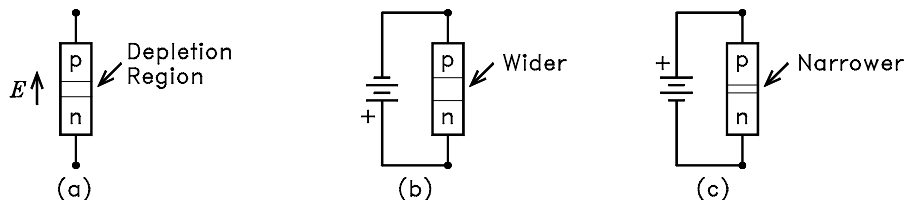


Figure 1: (a) Diode cross section. (b) Reverse biased diode. (c) Forward biased diode.

Figure 1(b) shows the diode with a battery connected across it. The polarity of the battery is such that it reinforces the electric field across the junction causing the depletion region to widen. The positive terminal pulls electrons in the n-type side away from the junction. The negative terminal pulls holes in the p-type side away from the junction. No current can flow. The diode is said to be reverse biased. Figure 1(c) shows the diode with the battery polarity reversed. The battery now tends to cancel out the electric field in the depletion region, causing its width to decrease. The positive terminal forces holes toward the junction. The negative terminal forces electrons toward the junction. A current flows which increases rapidly if the applied voltage is increased. The diode is said to be forward biased.

### $i - v$ Characteristics

Figure 2(a) shows the circuit symbol for the diode. The arrow part of the symbol points in the direction of current flow when the diode is forward biased. The upper terminal is called the anode. The lower terminal is called the cathode. These names come from vacuum tube diodes.

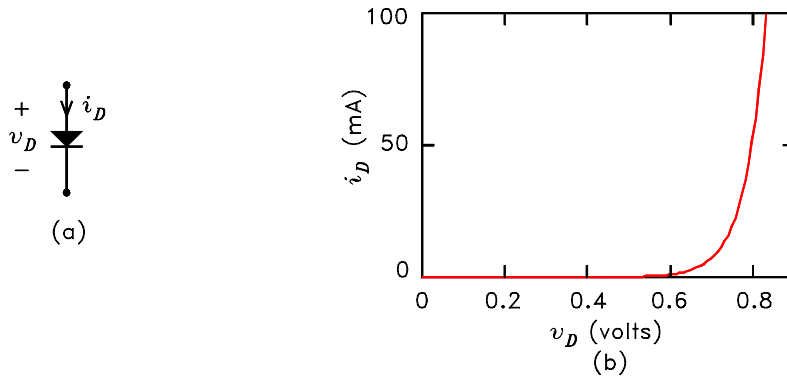


Figure 2: (a) Diode symbol. (b) Typical current versus voltage.

The theoretical equation for the diode current is

$$i_D = I_S \left[ \exp\left(\frac{v_D}{nV_T}\right) - 1 \right]$$

where  $I_S$  is the saturation current,  $n$  is the emission coefficient, and  $V_T$  is the thermal voltage. The emission coefficient accounts for recombinations of electrons and holes in the depletion region, which tend to decrease the current. For discrete diodes, it has the value  $n \simeq 2$ . For integrated circuit diodes, it has the value  $n \simeq 1$ . The reason it is different for the two cases is because an integrated circuit diode is fabricated as a bipolar transistor with the collector connected to the base. The impurity doping in transistors is done so as to minimize recombinations. Thus,  $n \simeq 1$  when recombinations can be neglected.

A typical plot of  $i_D$  versus  $v_D$  is given in Fig. 2(b). For  $v_D \leq 0.6$  V, the current is very small. For  $v_D > 0.6$  V, the current increases rapidly with  $v_D$ . The voltage at which the diode appears to begin conducting is called the cutin voltage. This is approximately 0.6 V for the plot in Fig. 2(b).

The thermal voltage is given by

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

where  $k$  is Boltzmann's constant,  $T$  is the Kelvin temperature, and  $q$  is the electronic charge. At  $T = 290$  K, the thermal voltage has the value  $V_T = 0.025$  V. The default value for  $T$  in SPICE is  $T = 300$  K. In this case, the thermal voltage has the value  $V_T = 0.02585$  V. This value should be used in any hand calculations that are to be compared to SPICE simulations. Because  $V_T$  increases with  $T$ , the equation for  $i_D$  seems to imply that increasing  $T$  decreases  $i_D$ . However,  $I_S$  increases rapidly with temperature which causes  $i_D$  to increase with  $T$ . A rule of thumb that is often quoted for silicon diodes is that if  $i_D$  is held constant,  $v_D$  decreases by about 2 mV for each degree C as  $T$  increases.

**Example 1** Calculate the amount by which  $v_D$  would have to be increased to double the diode current. Assume  $\exp(v_D/nV_T) \gg 1$  and  $V_T = 0.025$  V.

*Solution.* We have

$$2 = \frac{I_S [\exp(v_{D2}/nV_T) - 1]}{I_S [\exp(v_{D1}/nV_T) - 1]} \simeq \exp\left(\frac{v_{D2} - v_{D1}}{nV_T}\right)$$

Solution for  $\Delta v = v_{D2} - v_{D1}$  yields

$$\begin{aligned}\Delta v &= nV_T \ln 2 \\ &= 17.3 \text{ mV for } n = 1 \\ &= 34.7 \text{ mV for } n = 2\end{aligned}$$

This example illustrates how fast the diode current increases with increasing diode voltage.

### Linear Model

The linear model of the diode approximates the  $i - v$  characteristics by a straight line that is tangent to the actual curve at the dc bias point. Fig. 3(a) shows the curve with the tangent line at the point  $(V_D, I_D)$ . The curve intersects the horizontal axis at the voltage  $V_{DO}$ . For small changes in  $v_D$  and  $i_D$  about the tangent point, the tangent line gives a good approximation to the actual curve. The slope of the tangent line is given by

$$m = \left. \frac{di_D}{dv_D} \right|_{(V_D, I_D)} = \frac{1}{nV_T} I_S \exp\left(\frac{V_D}{nV_T}\right) = \frac{I_D + I_S}{nV_T} \approx \frac{1}{r_d}$$

where the units of  $r_d$  are ohms. The equation of the tangent line is

$$i_D = \frac{V_D - V_{DO}}{r_d}$$

The equivalent circuit which models this equation is shown in Fig. 3(b). Because  $v_D = V_D$  when  $i_D = I_D$ , it follows that the voltage  $V_{DO}$  is given by

$$V_{DO} = V_D - I_D r_d$$

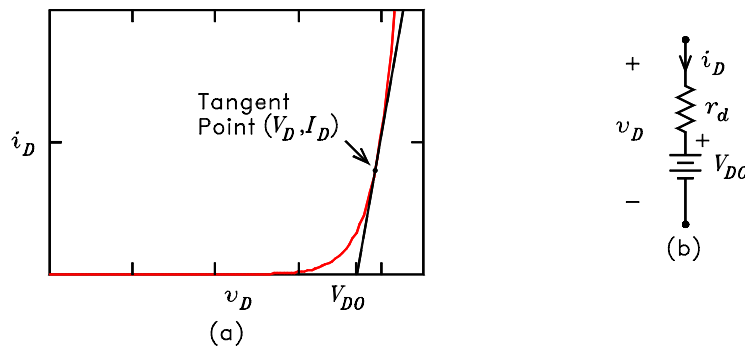


Figure 3: (a)  $i - v$  characteristics with tangent line at  $(V_D, I_D)$ . (b) Linear diode model.

**Example 2** A diode is biased at  $I_D = 1 \text{ mA}$ . It is given that  $I_S = 3.6 \times 10^{-9} \text{ A}$ ,  $n = 2$ , and  $V_T = 25.9 \text{ mV}$ . Solve for  $r_d$  and  $V_{DO}$  in the linear model.

*Solution.*  $V_D = nV_T \ln(I_D/I_S) = 0.649 \text{ V}$ ,  $r_d = nV_T/I_D = 51.8 \Omega$ ,  $V_{DO} = V_D - I_D r_d = 0.598 \text{ V}$ .

## Small-Signal Model

Because the diode equation for  $i_D$  as a function of  $v_D$  is non-linear, the tools of linear circuit analysis cannot be applied, in general, to circuits containing diodes. However, if the diode current is known for a particular voltage, linear circuit analysis can be used to predict the change in current for a given change in voltage, provided the change is not very large. Such an approach is called a small-signal analysis.

Let the diode voltage and current be written

$$v_D = V_D + v_d \quad i_D = I_D + i_d$$

where  $V_D$  and  $I_D$  are dc bias values and  $v_d$  and  $i_d$  are small-signal changes about the bias values. Let the diode equation be denoted by  $i_D = f(v_D)$  and its derivative denoted by  $di_D/dv_D = f'(v_D)$ . We can write

$$I_D + i_d = f(V_D + v_d) \simeq f(V_D) + f'(V_D)v_d$$

where the approximation is a first-order Taylor series expansion about the point  $(V_D, I_D)$ . Because  $I_D = f(V_D)$ , we can solve for  $i_d$  to obtain

$$i_d = f'(V_D)v_d = \frac{d}{dV_D} \left\{ I_S \left[ \exp\left(\frac{V_D}{nV_T}\right) - 1 \right] \right\} \times v_d = \frac{I_S}{V_T} \exp\left(\frac{V_D}{nV_T}\right) \times v_d = \frac{I_D + I_S}{nV_T} \times v_d$$

The small-signal resistance is defined as the ratio of  $v_d$  to  $i_d$  and is given by

$$r_d = \frac{nV_T}{I_D + I_S} \simeq \frac{nV_T}{I_D}$$

This is the same  $r_d$  as in the linear model of the diode in Fig. 3(b). Thus the small-signal model of the diode is a resistor of value  $r_d$ . The value of  $r_d$  is inversely proportional to the current through it. Each time the current is doubled, the resistance is halved. It follows from the linear diode model that  $r_d$  can be interpreted graphically as the reciprocal of the slope of the  $i_D$  versus  $v_D$  curve at the point  $(V_D, I_D)$ .

**Example 3** Figure 4(a) shows a diode attenuator circuit. The input voltage  $v_i$  is a small-signal differential voltage represented by two series sources with the common terminal grounded. The current  $I_Q$  is a dc control current. Solve for the small-signal gain  $v_o/v_i$ . Assume the diodes are identical,  $n = 2$ , and  $V_T = 0.025$  V.

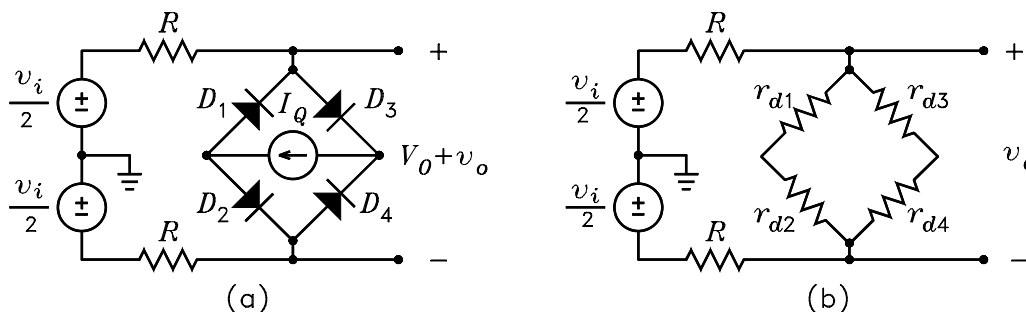


Figure 4: (a) Diode attenuator circuit. (b) Small-signal model.

*Solution.* For the dc solution, we set  $v_i = 0$ . In this case,  $v_o = 0$ . For identical diodes, the current  $I_Q$  splits equally between the upper diodes and the lower diodes, i.e. each diode has the

current  $I_Q/2$ . It follows the dc voltages across the diodes cancel in calculating  $V_O$  so that  $V_O = 0$ . The small-signal resistance of each diode is  $r_d = 2nV_T/I_Q = 0.1/I_Q$ . The small-signal circuit is shown in Fig. 4(b). The current  $I_Q$  does not appear in this circuit because it is a dc source which becomes an open circuit when zeroed. It follows by voltage division that

$$\frac{v_o}{v_i} = \frac{2r_d \parallel 2r_d}{2R + 2r_d \parallel 2r_d} = \frac{r_d}{2R + r_d} = \frac{0.1/I_Q}{2R + 0.1/I_Q} = \frac{1}{1 + 20I_Q R}$$

Thus the small-signal gain of the circuit can be varied by varying the dc current  $I_Q$ . A typical plot of the gain versus current for  $R = 10 \text{ k}\Omega$  is shown in Fig. 5. Over the range shown, the gain decreases by approximately 40 dB each time the control current increases by one decade.

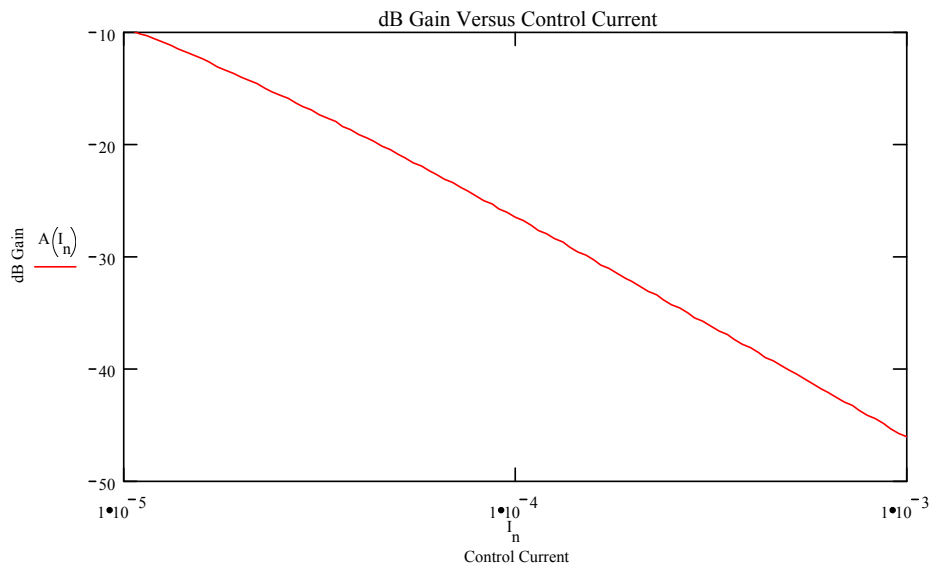


Figure 5: Gain in dB versus control current  $I_Q$ .