

## 5-1 The Zener Diode

Small-signal and rectifier diodes are never intentionally operated in the breakdown region because this may damage them. A **zener diode** is different; it is a silicon diode that the manufacturer has optimized for operation in the breakdown region. The zener diode is the backbone of voltage regulators, circuits that hold the load voltage almost constant despite large changes in line voltage and load resistance.

### I-V Graph

Figure 5-1a shows the schematic symbol of a zener diode; Fig. 5-1b is an alternative symbol. In either symbol, the lines resemble a z, which stands for “zener.” By varying the doping level of silicon diodes, a manufacturer can produce zener diodes with breakdown voltages from about 2 to over 1000 V. These diodes can operate in any of three regions: forward, leakage, and breakdown.

(Figure 5-1c shows the I-V graph of a zener diode. In the forward region, it starts conducting around 0.7 V, just like an ordinary silicon diode. In the **leakage region** (between zero and breakdown), it has only a small reverse current. In a zener diode, the breakdown has a very sharp knee, followed by an almost vertical increase in current.) Note that the voltage is almost constant, approximately equal to  $V_Z$  over most of the breakdown region. Data sheets usually specify the value of  $V_Z$  at a particular test current  $I_{ZT}$ .

(Figure 5-1c also shows the maximum reverse current  $I_{ZM}$ . As long as the reverse current is less than  $I_{ZM}$ , the diode is operating within its safe range. If the current is greater than  $I_{ZM}$ , the diode will be destroyed. To prevent excessive reverse current, a *current-limiting resistor* must be used (discussed later).)

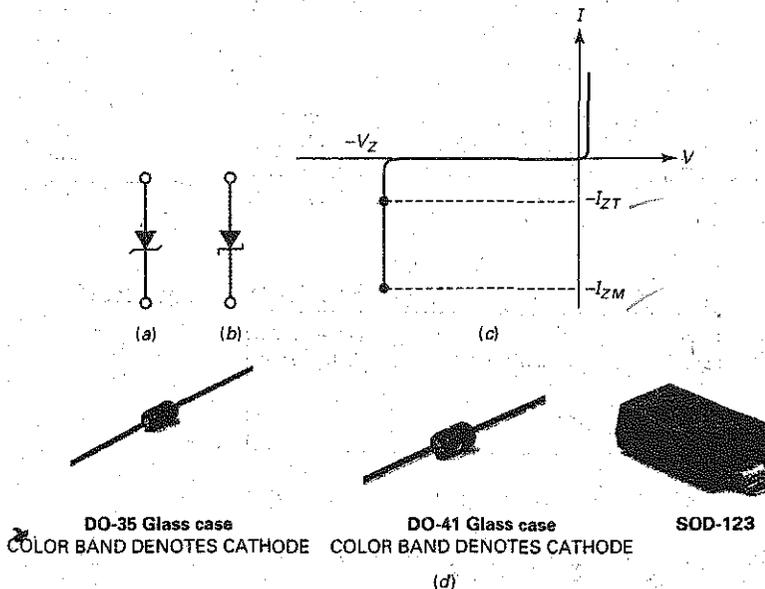
### Zener Resistance

In the third approximation of a silicon diode, the forward voltage across a diode equals the knee voltage plus the additional voltage across the bulk resistance.

### GOOD TO KNOW

As with conventional diodes, the manufacturer places a band on the cathode end of the zener diode for terminal identification.

**Figure 5-1** Zener diode. (a) Schematic symbol; (b) alternative symbol; (c) graph of current versus voltage; (d) typical zener diodes.



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Similarly, in the breakdown region, the reverse voltage across a diode equals the breakdown voltage plus the additional voltage across the bulk resistance. In the reverse region, the bulk resistance is referred to as the **zener resistance**. This resistance equals the inverse of the slope in the breakdown region. In other words, the more vertical the breakdown region, the smaller the zener resistance.

In Fig. 5-1c, the zener resistance means that an increase in reverse current produces a slight increase in reverse voltage. The increase in voltage is very small, typically only a few tenths of a volt. This slight increase may be important in design work, but not in troubleshooting and preliminary analysis. Unless otherwise indicated, our discussions will ignore the zener resistance. Fig. 5-1(d) shows typical zener diodes.

## Zener Regulator

A zener diode is sometimes called a *voltage-regulator diode* because it maintains a constant output voltage even though the current through it changes. For normal operation, you have to reverse bias the zener diode, as shown in Fig. 5-2a. Furthermore, to get breakdown operation, the source voltage  $V_S$  must be greater than the zener breakdown voltage  $V_Z$ . A series resistor  $R_S$  is always used to limit the zener current to less than its maximum current rating. Otherwise, the zener diode will burn out like any device with too much power dissipation.)

Figure 5-2b shows an alternative way to draw the circuit with grounds. Whenever a circuit has grounds, you can measure voltages with respect to ground.

For instance, suppose you want to know the voltage across the series resistor of Fig. 5-2b. Here is the one way to find it when you have a built-up circuit. First, measure the voltage from the left end of  $R_S$  to ground. Second, measure the voltage from the right end of  $R_S$  to ground. Third, subtract the two voltages to get the voltage across  $R_S$ . If you have a floating VOM or DMM, you can connect directly across the series resistor.

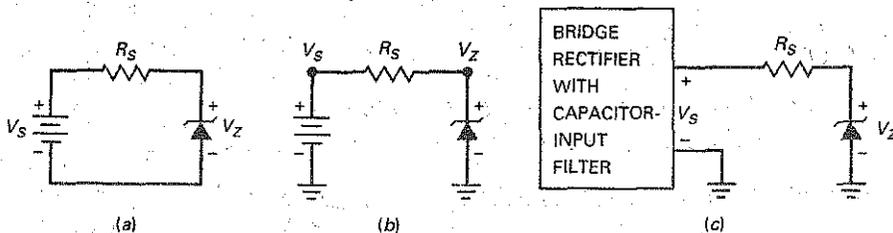
Figure 5-2c shows the output of a power supply connected to a series resistor and a zener diode. This circuit is used when you want a dc output voltage that is less than the output of the power supply. A circuit like this is called a *zener voltage regulator*, or simply a **zener regulator**.

## Ohm's Law Again

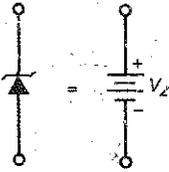
In Fig. 5-2, the voltage across the series or current-limiting resistor equals the difference between the source voltage and the zener voltage. Therefore, the current through the resistor is

$$I_S = \frac{V_S - V_Z}{R_S} \quad (5-1)$$

**Figure 5-2** Zener regulator. (a) Basic circuit; (b) same circuit with grounds; (c) power supply drives regulator.



**Figure 5-3** Ideal approximation of a zener diode.



Once you have the value of series current, you also have the value of zener current. This is because Fig. 5-2 is a series circuit. Note that  $I_S$  must be less than  $I_{ZM}$ .

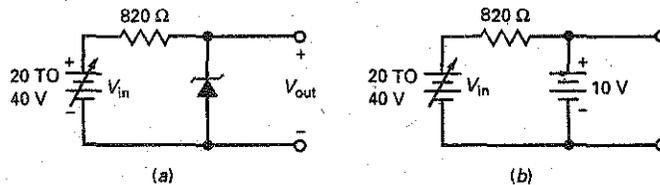
### Ideal Zener Diode

For troubleshooting and preliminary analysis, we can approximate the breakdown region as vertical. Therefore, the voltage is constant even though the current changes, which is equivalent to ignoring the zener resistance. Figure 5-3 shows the ideal approximation of a zener diode. This means that a zener diode operating in the breakdown region ideally acts like a battery. In a circuit, it means that you can mentally replace a zener diode by a voltage source of  $V_Z$ , provided the zener diode is operating in the breakdown region.

### Example 5-1

Suppose the zener diode of Fig. 5-4a has a breakdown voltage of 10 V. What are the minimum and maximum zener currents?

**Figure 5-4** Example.



**SOLUTION** The applied voltage may vary from 20 to 40 V. Ideally, a zener diode acts like the battery shown in Fig. 5-4b. Therefore, the output voltage is 10 V for any source voltage between 20 and 40 V.

The minimum current occurs when the source voltage is minimum. Visualize 20 V on the left end of the resistor and 10 V on the right end. Then you can see that the voltage across the resistor is 20 V - 10 V, or 10 V. The rest is Ohm's law:

$$I_S = \frac{10 \text{ V}}{820 \Omega} = 12.2 \text{ mA}$$

The maximum current occurs when the source voltage is 40 V. In this case, the voltage across the resistor is 30 V, which gives a current of

$$I_S = \frac{30 \text{ V}}{820 \Omega} = 36.6 \text{ mA}$$

In a voltage regulator like Fig. 5-4a, the output voltage is held constant at 10 V, despite the change in source voltage from 20 to 40 V. The larger source voltage produces more zener current, but the output voltage holds rock-solid at 10 V. (If the zener resistance is included, the output voltage increases slightly when the source voltage increases.)

**PRACTICE PROBLEM 5-1** Using Fig. 5-4, what is the zener current  $I_S$  if  $V_{in} = 30 \text{ V}$ ?