3 SPECIAL-PURPOSE DIODES

CHAPTER OUTLINE

3–1 The Zener Diode
3–2 Zener Diode Applications
3–3 The Varactor Diode
3–4 Optical Diodes
3–5 Other Types of Diodes
3–6 Troubleshooting
Application Activity
Green Tech Application 3: *Solar Power*

CHAPTER OBJECTIVES

- Describe the characteristics of a zener diode and analyze its operation
- Apply a zener diode in voltage regulation
- Describe the varactor diode characteristic and analyze its operation
- Discuss the characteristics, operation, and applications of LEDs, quantum dots, and photodiodes
- Discuss the basic characteristics of several types of diodes
- Troubleshoot zener diode regulators

KEY TERMS

- Zener diode
- Zener breakdown
- Varactor
- Light-emitting diode (LED)
- Electroluminescence
- Pixel
- Photodiode
- Laser

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INTRODUCTION

Chapter 2 was devoted to general-purpose and rectifier diodes, which are the most widely used types. In this chapter, we will cover several other types of diodes that are designed for specific applications, including the zener, varactor (variable-capacitance), light-emitting, photo, laser, Schottky, tunnel, *pin,* step-recovery, and current regulator diodes.

APPLICATION ACTIVITY PREVIEW

The Application Activity in this chapter is the expansion of the 16 V power supply developed in Chapter 2 into a 12 V regulated power supply with an LED power-on indicator. The new circuit will incorporate a voltage regulator IC, which is introduced in this chapter.

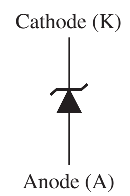
3–1 THE ZENER DIODE

A major application for zener diodes is as a type of voltage regulator for providing stable reference voltages for use in power supplies, voltmeters, and other instruments. In this section, you will see how the zener diode maintains a nearly constant dc voltage under the proper operating conditions. You will learn the conditions and limitations for properly using the zener diode and the factors that affect its performance.

After completing this section, you should be able to

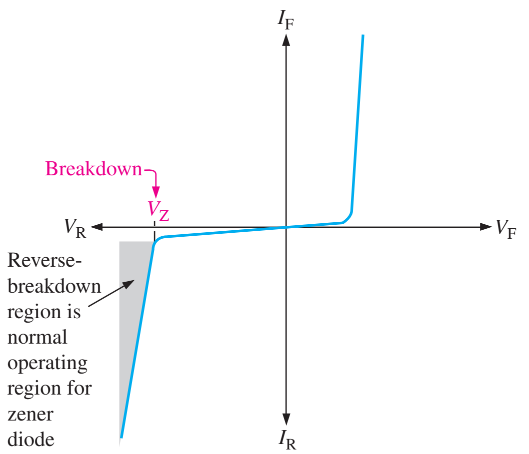
- **Describe the characteristics of a zener diode and analyze its operation**
- Recognize a zener diode by its schematic symbol
- Discuss zener breakdown
  - Define *avalanche breakdown*
- Explain zener breakdown characteristics
  - Describe zener regulation
- Discuss zener equivalent circuits
- Define *temperature coefficient*
  - Analyze zener voltage as a function of temperature
- Discuss zener power dissipation and derating
  - Apply power derating to a zener diode
- Interpret zener diode datasheets

The symbol for a zener diode is shown in Figure 3–1. Instead of a straight line representing the cathode, the zener diode has a bent line that reminds you of the letter Z (for zener). A **zener diode** is a silicon *pn* junction device that is designed for operation in the reverse-breakdown region. The breakdown voltage of a zener diode is set by carefully controlling the doping level during manufacture. Recall, from the discussion of the diode characteristic curve in Chapter 2, that when a diode reaches reverse breakdown, its voltage remains almost constant even though the current changes drastically, and this is the key to zener diode operation. This volt-ampere characteristic is shown again in Figure 3–2 with the normal operating region for zener diodes shown as a shaded area.



▲ FIGURE 3–1

Zener diode symbol.



◀ FIGURE 3–2

General zener diode *V-I* characteristic.

Zener Breakdown

Zener diodes are designed to operate in reverse breakdown. Two types of reverse breakdown in a zener diode are *avalanche* and *zener.* The avalanche effect, discussed in Chapter 2, occurs in both rectifier and zener diodes at a sufficiently high reverse voltage. **Zener breakdown**

HISTORY NOTE

Clarence Melvin Zener, an American physicist, was born in Indianapolis and earned his PhD from Harvard in 1930. He was the first to describe the properties of reverse breakdown that are exploited by the zener diode. As a result, Bell Labs, where the device was developed, named the diode after him. He was also involved in areas of superconductivity, metallurgy, and geometric programming.

occurs in a zener diode at low reverse voltages. A zener diode is heavily doped to reduce the breakdown voltage. This causes a very thin depletion region. As a result, an intense electric field exists within the depletion region. Near the zener breakdown voltage (V_Z), the field is intense enough to pull electrons from their valence bands and create current.

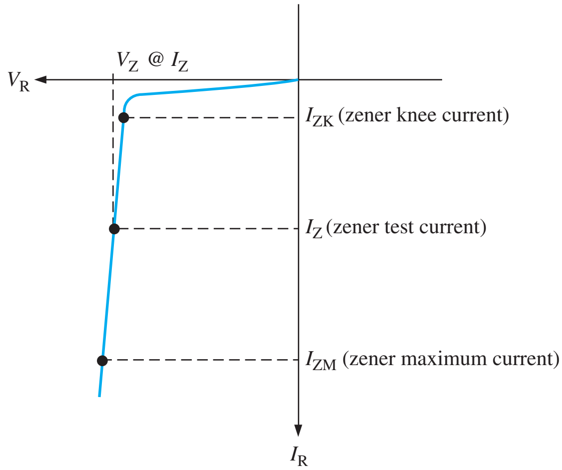
Zener diodes with breakdown voltages of less than approximately 5 V operate predominately in zener breakdown. Those with breakdown voltages greater than approximately 5 V operate predominately in **avalanche breakdown.** Both types, however, are called *zener diodes.* Zeners are commercially available with breakdown voltages from less than 1 V to more than 250 V with specified tolerances from 1% to 20%.

Breakdown Characteristics

Figure 3–3 shows the reverse portion of a zener diode's characteristic curve. Notice that as the reverse voltage (V_R) is increased, the reverse current (I_R) remains extremely small up to the "knee" of the curve. The reverse current is also called the zener current, I_Z. At this point, the breakdown effect begins; the internal zener resistance, also called zener impedance (Z_Z), begins to decrease as the reverse current increases rapidly. From the bottom of the knee, the zener breakdown voltage (V_Z) remains essentially constant although it increases slightly as the zener current, I_Z, increases.

FIGURE 3–3

Reverse characteristic of a zener diode. V_Z is usually specified at a value of the zener current known as the test current.

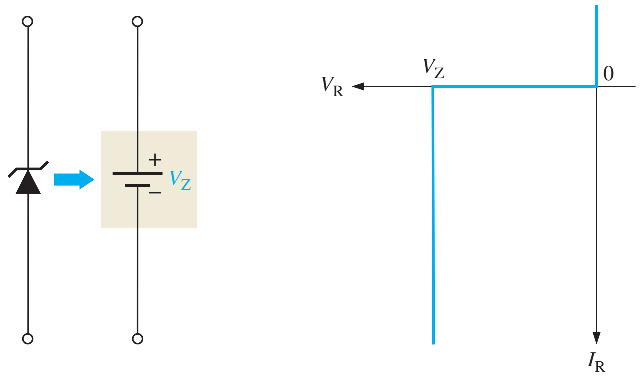


Zener Regulation The ability to keep the reverse voltage across its terminals essentially constant is the key feature of the zener diode. A zener diode operating in breakdown acts as a voltage regulator because it maintains a nearly constant voltage across its terminals over a specified range of reverse-current values.

A minimum value of reverse current, I_{ZK}, must be maintained in order to keep the diode in breakdown for voltage regulation. You can see on the curve in Figure 3–3 that when the reverse current is reduced below the knee of the curve, the voltage decreases drastically and regulation is lost. Also, there is a maximum current, I_{ZM}, above which the diode may be damaged due to excessive power dissipation. So, basically, the zener diode maintains a nearly constant voltage across its terminals for values of reverse current ranging from I_{ZK} to I_{ZM}. A nominal zener voltage, V_Z, is usually specified on a datasheet at a value of reverse current called the *zener test current.*

Zener Equivalent Circuits

Figure 3–4 shows the ideal model (first approximation) of a zener diode in reverse breakdown and its ideal characteristic curve. It has a constant voltage drop equal to the nominal zener voltage. This constant voltage drop across the zener diode produced by reverse breakdown is represented by a dc voltage symbol even though the zener diode does not produce a voltage.



(a) Ideal model (b) Ideal characteristic curve

FIGURE 3–4

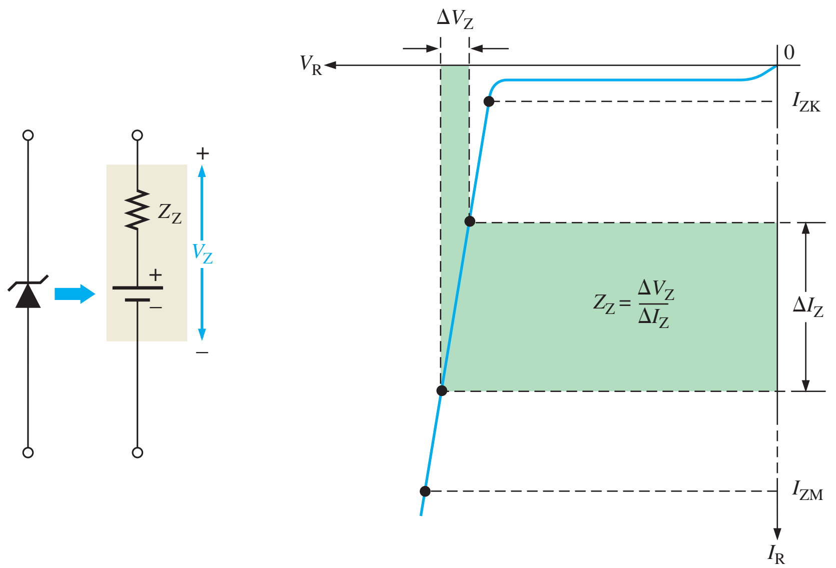
Ideal zener diode equivalent circuit model and the characteristic curve.

Figure 3–5(a) represents the practical model (second approximation) of a zener diode, where the zener impedance (resistance), Z_Z, is included. Since the actual voltage curve is not ideally vertical, a change in zener current (ΔI_Z) produces a small change in zener voltage (ΔV_Z), as illustrated in Figure 3–5(b). By Ohm's law, the ratio of ΔV_Z to ΔI_Z is the impedance, as expressed in the following equation:

$$\mathbf{Z_Z = \frac{\Delta V_Z}{\Delta I_Z}}$$

Equation 3–1

Normally, Z_Z is specified at the zener test current. In most cases, you can assume that Z_Z is a small constant over the full range of zener current values and is purely resistive. It is best to avoid operating a zener diode near the knee of the curve because the impedance changes dramatically in that area.



(a) Practical model (b) Characteristic curve. The slope is exaggerated for illustration.

FIGURE 3–5

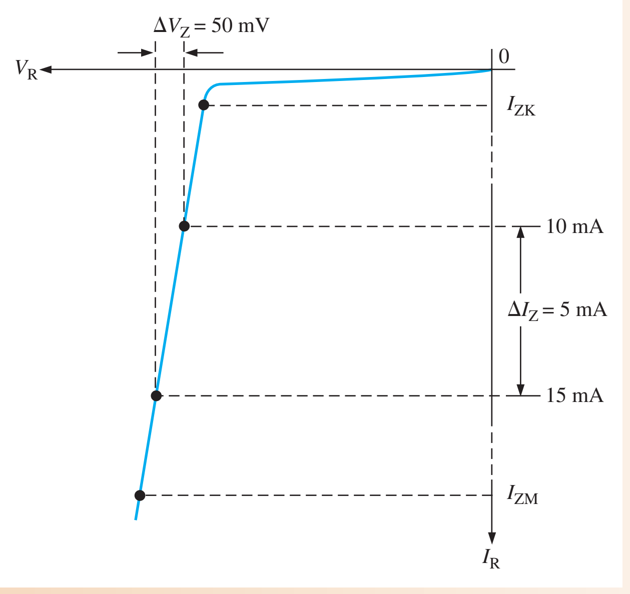
Practical zener diode equivalent circuit and the characteristic curve illustrating Z_Z.

For most circuit analysis and troubleshooting work, the ideal model will give very good results and is much easier to use than more complicated models. When a zener diode is operating normally, it will be in reverse breakdown and you should observe the nominal breakdown voltage across it. Most **schematics** will indicate on the drawing what this voltage should be.

EXAMPLE 3–1

A zener diode exhibits a certain change in V_Z for a certain change in I_Z on a portion of the linear characteristic curve between I_{ZK} and I_{ZM} as illustrated in Figure 3–6. What is the zener impedance?

▶ FIGURE 3–6



Solution

$$Z_Z = \frac{\Delta V_Z}{\Delta I_Z} = \frac{50\text{ mV}}{5\text{ mA}} = \mathbf{10\ \Omega}$$

*Related Problem** Calculate the zener impedance if the change in zener voltage is 100 mV for a 20 mA change in zener current on the linear portion of the characteristic curve.

***Answers can be found at www.pearsonhighered.com/floyd.**

Temperature Coefficient

The temperature coefficient specifies the percent change in zener voltage for each degree Celsius change in temperature. For example, a 12 V zener diode with a positive temperature coefficient of 0.01%/°C will exhibit a 1.2 mV increase in V_Z when the junction temperature increases one degree Celsius. The formula for calculating the change in zener voltage for a given junction temperature change, for a specified temperature coefficient, is

Equation 3–2

$$\Delta V_Z = V_Z \times TC \times \Delta T$$

where V_Z is the nominal zener voltage at the reference temperature of 25°C, TC is the temperature coefficient, and ΔT is the change in temperature from the reference temperature. A positive TC means that the zener voltage increases with an increase in temperature or decreases with a decrease in temperature. A negative TC means that the zener voltage decreases with an increase in temperature or increases with a decrease in temperature.

In some cases, the temperature coefficient is expressed in mV/°C rather than as %/°C. For these cases, ΔV_Z is calculated as

Equation 3–3

$$\Delta V_Z = TC \times \Delta T$$

EXAMPLE 3–2 An 8.2 V zener diode (8.2 V at 25°C) has a positive temperature coefficient of 0.05%/°C. What is the zener voltage at 60°C?

Solution The change in zener voltage is

$$\Delta V_Z = V_Z \times TC \times \Delta T = (8.2\text{ V})(0.05\%/°\text{C})(60°\text{C} - 25°\text{C})$$
$$= (8.2\text{ V})(0.0005/°\text{C})(35°\text{C}) = 144\text{ mV}$$

Notice that 0.05%/°C was converted to 0.0005/°C. The zener voltage at 60°C is

$$V_Z + \Delta V_Z = 8.2\text{ V} + 144\text{ mV} = \mathbf{8.34\text{ V}}$$

Related Problem A 12 V zener has a positive temperature coefficient of 0.075%/°C. How much will the zener voltage change when the junction temperature decreases 50 degrees Celsius?

Zener Power Dissipation and Derating

Zener diodes are specified to operate at a maximum power called the maximum dc power dissipation, $P_{D(max)}$. For example, the 1N746 zener is rated at a $P_{D(max)}$ of 500 mW and the 1N3305A is rated at a $P_{D(max)}$ of 50 W. The dc power dissipation is determined by the formula,

$$P_D = V_Z I_Z$$

Power Derating The maximum power dissipation of a zener diode is typically specified for temperatures at or below a certain value (50°C, for example). Above the specified temperature, the maximum power dissipation is reduced according to a derating factor. The derating factor is expressed in mW/°C. The maximum derated power can be determined with the following formula:

$$P_{D(derated)} = P_{D(max)} - (\text{mW}/°\text{C})\Delta T$$

EXAMPLE 3–3 A certain zener diode has a maximum power rating of 400 mW at 50°C and a derating factor of 3.2 mW/°C. Determine the maximum power the zener can dissipate at a temperature of 90°C.

Solution

$$P_{D(derated)} = P_{D(max)} - (\text{mW}/°\text{C})\Delta T$$
$$= 400\text{ mW} - (3.2\text{ mW}/°\text{C})(90°\text{C} - 50°\text{C})$$
$$= 400\text{ mW} - 128\text{ mW} = \mathbf{272\text{ mW}}$$

Related Problem A certain 50 W zener diode must be derated with a derating factor of 0.5 W/°C above 75°C. Determine the maximum power it can dissipate at 160°C.

Zener Diode Datasheet Information

The amount and type of information found on datasheets for zener diodes (or any category of electronic device) varies from one type of diode to the next. The datasheet for some zeners contains more information than for others. Figure 3–7 gives an example of the type of information you have studied that can be found on a typical datasheet. This particular information is for a zener series, the 1N4728A–1N4764A.