3. What causes the ripple voltage on the output of a capacitor-input filter?
4. If the load resistance connected to a filtered power supply is decreased, what happens to the ripple voltage?
5. Define *ripple factor.*
6. What is the difference between input (line) regulation and load regulation?

## 2–7 DIODE LIMITERS AND CLAMPERS

Diode circuits, called limiters or clippers, are sometimes used to clip off portions of signal voltages above or below certain levels. Another type of diode circuit, called a clamper, is used to add or restore a dc level to an electrical signal. Both limiter and clamper diode circuits will be examined in this section.

After completing this section, you should be able to

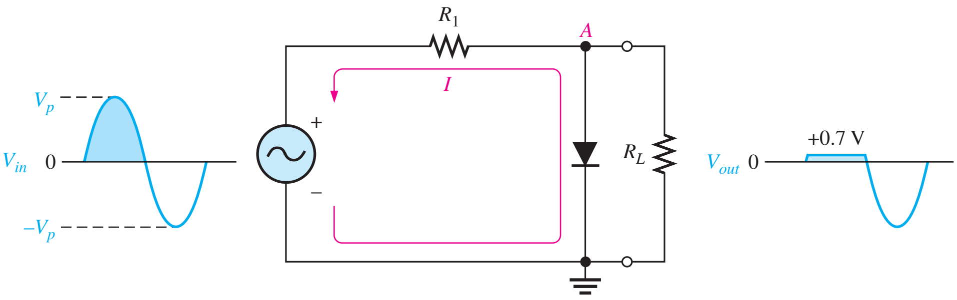
- **Explain and analyze the operation of diode limiters and clampers**
- Describe the operation of a diode limiter
  - ◆ Discuss biased limiters ◆ Discuss voltage-divider bias ◆ Describe an application
- Describe the operation of a diode clamper

### Diode Limiters

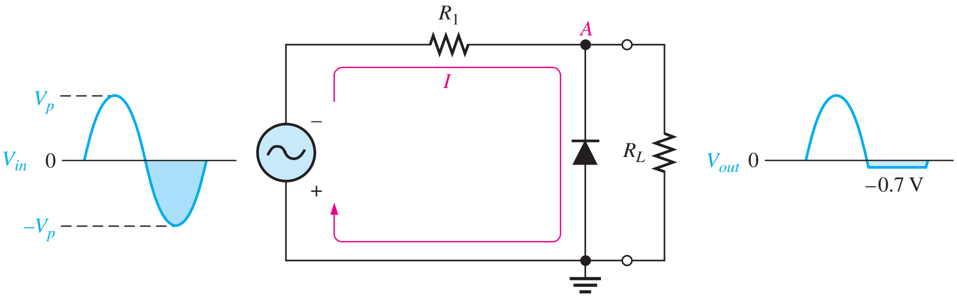
Figure 2–52(a) shows a diode positive **limiter** (also called **clipper**) that limits or clips the positive part of the input voltage. As the input voltage goes positive, the diode becomes forward-biased and conducts current. Point $A$ is limited to $+0.7$ V when the input voltage exceeds this

▶ FIGURE 2–52

Examples of diode limiters (clippers).



(a) Limiting of the positive alternation. The diode is forward-biased during the positive alternation (above 0.7 V) and reverse-biased during the negative alternation.



(b) Limiting of the negative alternation. The diode is forward-biased during the negative alternation (below −0.7 V) and reverse-biased during the positive alternation.

value. When the input voltage goes back below 0.7 V, the diode is reverse-biased and appears as an open. The output voltage looks like the negative part of the input voltage, but with a magnitude determined by the voltage divider formed by $R_1$ and the load resistor, $R_L$, as follows:

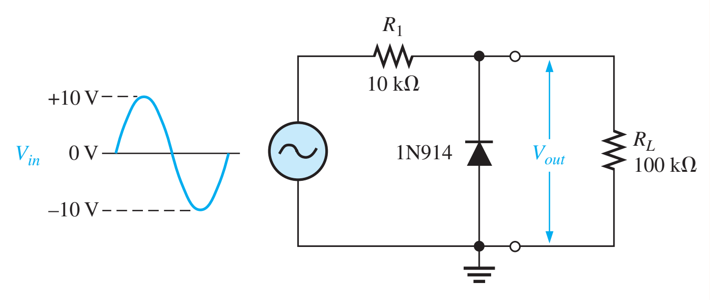
$$V_{out} = \left(\frac{R_L}{R_1 + R_L}\right)V_{in}$$

If $R_1$ is small compared to $R_L$, then $V_{out} \cong V_{in}$.

If the diode is turned around, as in Figure 2–52(b), the negative part of the input voltage is clipped off. When the diode is forward-biased during the negative part of the input voltage, point $A$ is held at $-0.7$ V by the diode drop. When the input voltage goes above $-0.7$ V, the diode is no longer forward-biased; and a voltage appears across $R_L$ proportional to the input voltage.

**EXAMPLE 2–10**

What would you expect to see displayed on an oscilloscope connected across $R_L$ in the limiter shown in Figure 2–53?

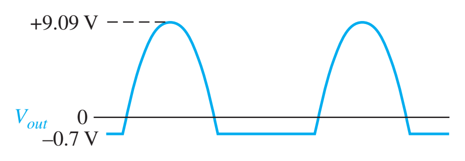


▶ FIGURE 2–53

*Solution* The diode is forward-biased and conducts when the input voltage goes below $-0.7$ V. So, for the negative limiter, determine the peak output voltage across $R_L$ by the following equation:

$$V_{p(out)} = \left(\frac{R_L}{R_1 + R_L}\right)V_{p(in)} = \left(\frac{100\text{ k}\Omega}{110\text{ k}\Omega}\right)10\text{ V} = 9.09\text{ V}$$

The scope will display an output waveform as shown in Figure 2–54.



▶ FIGURE 2–54

**Output voltage waveform for Figure 2–53.**

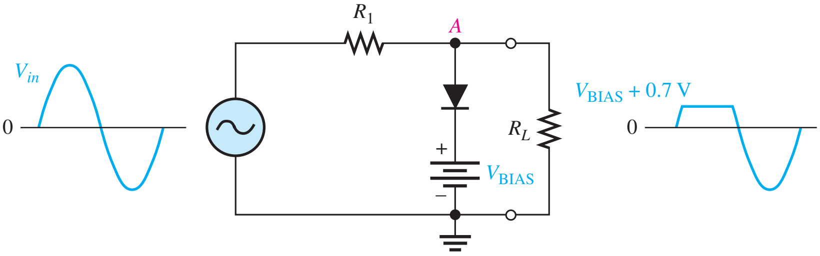
*Related Problem* Describe the output waveform for Figure 2–53 if $R_1$ is changed to 1 kΩ.

Open the Multisim file E02-10 in the Examples folder on the companion website. For the specified input, measure the resulting output waveform. Compare with the waveform shown in the example.

**Biased Limiters** The level to which an ac voltage is limited can be adjusted by adding a bias voltage, $V_{BIAS}$, in series with the diode, as shown in Figure 2–55. The voltage at point $A$ must equal $V_{BIAS} + 0.7$ V before the diode will become forward-biased and conduct. Once the diode begins to conduct, the voltage at point $A$ is limited to $V_{BIAS} + 0.7$ V so that all input voltage above this level is clipped off.

**FIGURE 2–55**

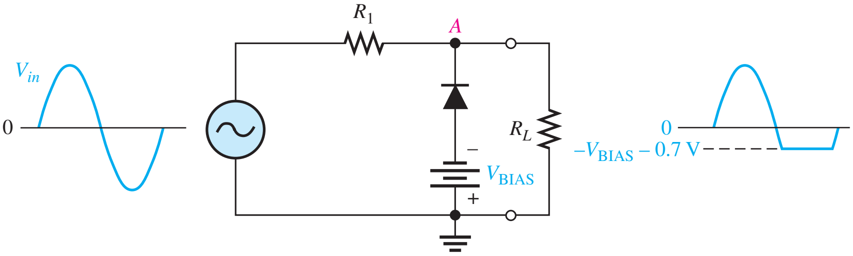
A positive limiter.



To limit a voltage to a specified negative level, the diode and bias voltage must be connected as in Figure 2–56. In this case, the voltage at point $A$ must go below $-V_{BIAS} - 0.7$ V to forward-bias the diode and initiate limiting action as shown.

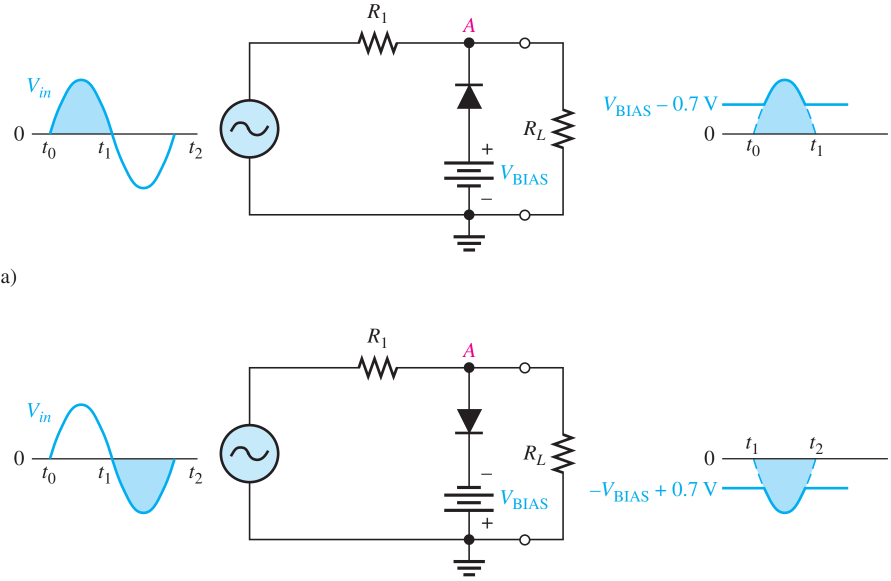
**FIGURE 2–56**

A negative limiter.



By turning the diode around, the positive limiter can be modified to limit the output voltage to the portion of the input voltage waveform above $V_{BIAS} - 0.7$ V, as shown by the output waveform in Figure 2–57(a). Similarly, the negative limiter can be modified to limit the output voltage to the portion of the input voltage waveform below $-V_{BIAS} + 0.7$ V, as shown by the output waveform in part (b).

**FIGURE 2–57**



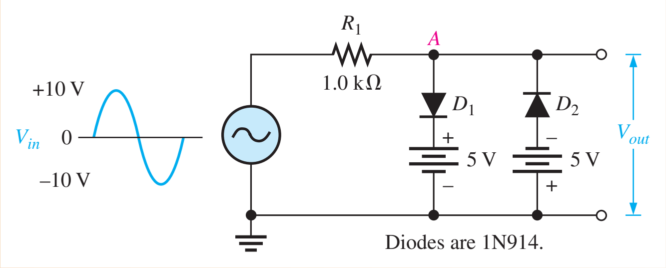
(a)

(b)

**EXAMPLE 2–11**

Figure 2–58 shows a circuit combining a positive limiter with a negative limiter. Determine the output voltage waveform.

**FIGURE 2–58**

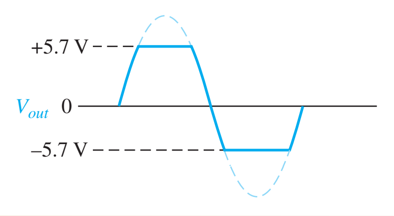


Diodes are 1N914.

*Solution* When the voltage at point $A$ reaches +5.7 V, diode $D_1$ conducts and limits the waveform to +5.7 V. Diode $D_2$ does not conduct until the voltage reaches −5.7 V. Therefore, positive voltages above +5.7 V and negative voltages below −5.7 V are clipped off. The resulting output voltage waveform is shown in Figure 2–59.

**FIGURE 2–59**

**Output voltage waveform for Figure 2–58.**



*Related Problem* Determine the output voltage waveform in Figure 2–58 if both dc sources are 10 V and the input voltage has a peak value of 20 V.

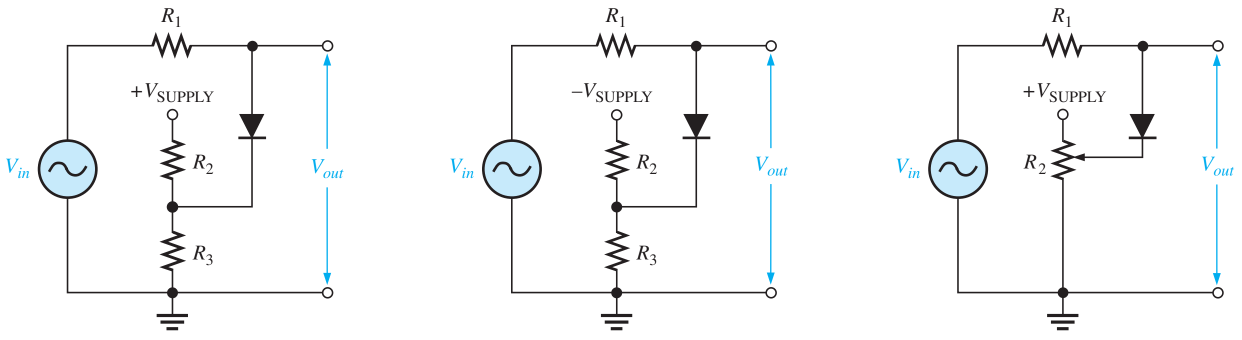
Open the Multisim file E02-11 in the Examples folder on the companion website. For the specified input, measure the resulting output waveform. Compare with the waveform shown in the example.

***Voltage-Divider Bias*** The bias voltage sources that have been used to illustrate the basic operation of diode limiters can be replaced by a resistive voltage divider that derives the desired bias voltage from the dc supply voltage, as shown in Figure 2–60. The bias voltage is set by the resistor values according to the voltage-divider formula.

$$V_{\text{BIAS}} = \left(\frac{R_3}{R_2 + R_3}\right)V_{\text{SUPPLY}}$$

A positively biased limiter is shown in Figure 2–60(a), a negatively biased limiter is shown in part (b), and a variable positive bias circuit using a potentiometer voltage divider is shown in part (c). The bias resistors must be small compared to $R_1$ so that the forward current through the diode will not affect the bias voltage.

***A Limiter Application*** Many circuits have certain restrictions on the input level to avoid damaging the circuit. For example, almost all digital circuits should not have an input level that exceeds the power supply voltage. An input of a few volts more than this could damage the circuit. To prevent the input from exceeding a specific level, you may see a diode limiter across the input signal path in many digital circuits.



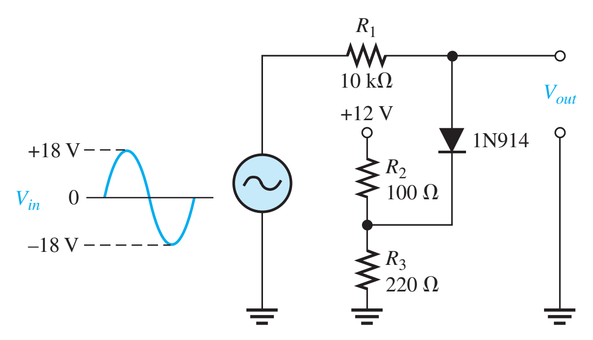
(a) Positive limiter (b) Negative limiter (c) Variable positive limiter

▲ **FIGURE 2–60**

Diode limiters implemented with voltage-divider bias.

**EXAMPLE 2–12** Describe the output voltage waveform for the diode limiter in Figure 2–61.

▶ **FIGURE 2–61**

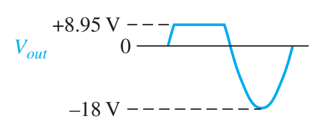


*Solution* The circuit is a positive limiter. Use the voltage-divider formula to determine the bias voltage.

$$V_{\text{BIAS}} = \left(\frac{R_3}{R_2 + R_3}\right)V_{\text{SUPPLY}} = \left(\frac{220\ \Omega}{100\ \Omega + 220\ \Omega}\right)12\ \text{V} = 8.25\ \text{V}$$

The output voltage waveform is shown in Figure 2–62. The positive part of the output voltage waveform is limited to $V_{\text{BIAS}} + 0.7$ V.

▶ **FIGURE 2–62**



*Related Problem* How would you change the voltage divider in Figure 2–61 to limit the output voltage to +6.7 V?

Open the Multisim file E02-12 in the Examples folder on the companion website. Observe the output voltage on the oscilloscope and compare to the calculated result.

## Diode Clampers

A clamper adds a dc level to an ac voltage. **Clampers** are sometimes known as *dc restorers*. Figure 2–63 shows a diode clamper that inserts a positive dc level in the output waveform. The operation of this circuit can be seen by considering the first negative half-cycle of the input voltage. When the input voltage initially goes negative, the diode is forward-biased, allowing the capacitor to charge to near the peak of the input ($V_{p(in)} - 0.7$ V), as shown in Figure 2–63(a). Just after the negative peak, the diode is reverse-biased. This is because the cathode is held near $V_{p(in)} - 0.7$ V by the charge on the capacitor. The capacitor can only discharge through the high resistance of $R_L$. So, from the peak of one negative half-cycle to the next, the capacitor discharges very little. The amount that is discharged, of course, depends on the value of $R_L$.

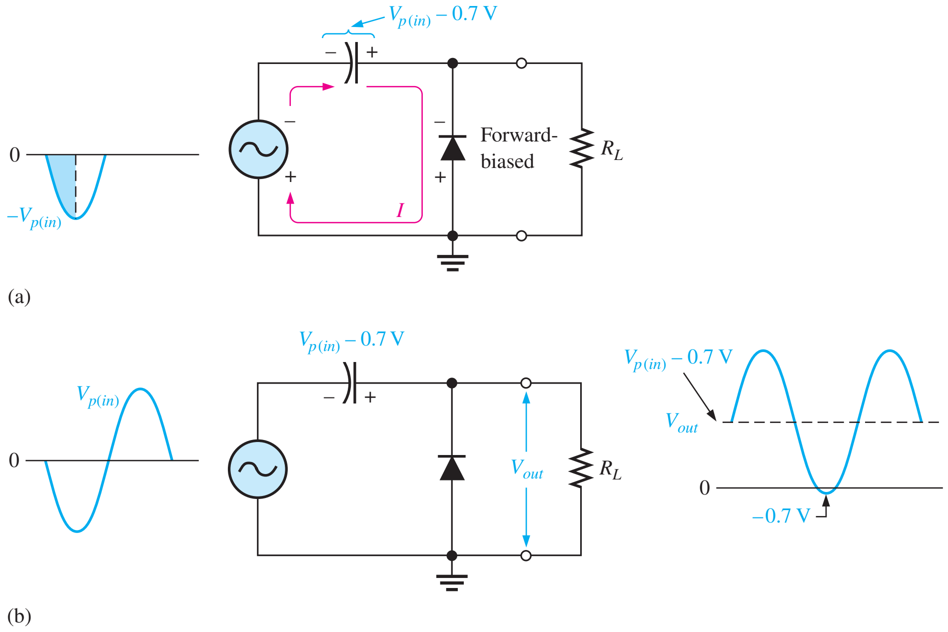


**FIGURE 2–63**

Positive clamper operation.

If the capacitor discharges during the period of the input wave, clamping action is affected. If the *RC* time constant is 100 times the period, the clamping action is excellent. An *RC* time constant of ten times the period will have a small amount of distortion at the ground level due to the charging current.

The net effect of the clamping action is that the capacitor retains a charge approximately equal to the peak value of the input less the diode drop. The capacitor voltage acts essentially as a battery in series with the input voltage. The dc voltage of the capacitor adds to the input voltage by superposition, as in Figure 2–63(b).

If the diode is turned around, a negative dc voltage is added to the input voltage to produce the output voltage as shown in Figure 2–64.

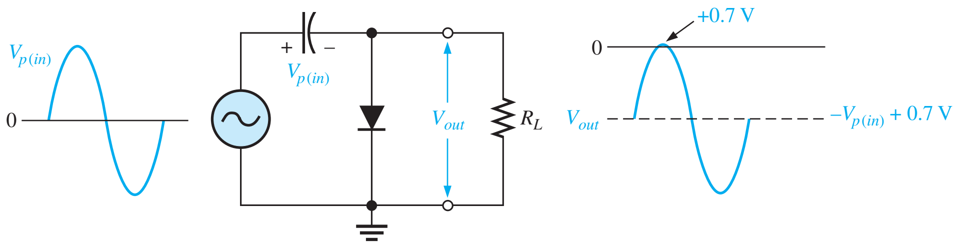


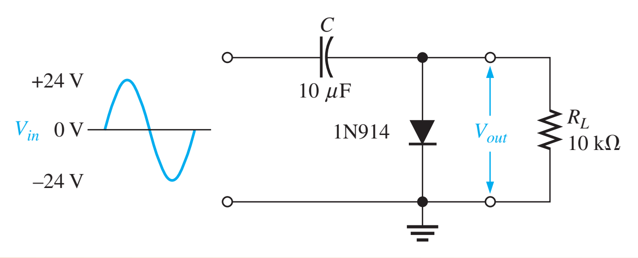
**FIGURE 2–64**

Negative clamper.

**EXAMPLE 2–13**

What is the output voltage that you would expect to observe across $R_L$ in the clamping circuit of Figure 2–65? Assume that $RC$ is large enough to prevent significant capacitor discharge.

**FIGURE 2–65**



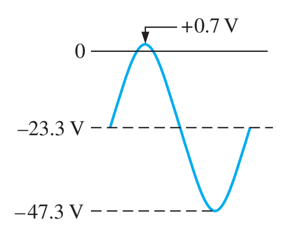
*Solution* Ideally, a negative dc value equal to the input peak less the diode drop is inserted by the clamping circuit.

$$V_{\text{DC}} \cong -(V_{p(in)} - 0.7\text{ V}) = -(24\text{ V} - 0.7\text{ V}) = \mathbf{-23.3\text{ V}}$$

Actually, the capacitor will discharge slightly between peaks, and, as a result, the output voltage will have an average value of slightly less than that calculated above. The output waveform goes to approximately +0.7 V, as shown in Figure 2–66.

**FIGURE 2–66**

Output waveform across $R_L$ for Figure 2–65.



*Related Problem* What is the output voltage that you would observe across $R_L$ in Figure 2–65 for $C = 22\ \mu\text{F}$ and $R_L = 18\text{ k}\Omega$?

Open the Multisim file E02-13 in the Examples folder on the companion website. For the specified input, measure the output waveform. Compare with the waveform shown in the example.

**SECTION 2–7 CHECKUP**

1. Discuss how diode limiters and diode clampers differ in terms of their function.
2. What is the difference between a positive limiter and a negative limiter?
3. What is the maximum voltage across an unbiased positive silicon diode limiter during the positive alternation of the input voltage?
4. To limit the output voltage of a positive limiter to 5 V when a 10 V peak input is applied, what value must the bias voltage be?
5. What component in a clamping circuit effectively acts as a battery?

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%.

### HISTORY NOTE

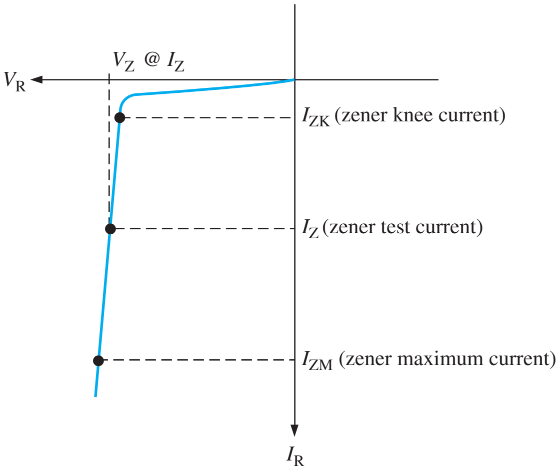
Clarence Melvin Zener, an American physicist, was born in Indianapolis and earned his PhD from Harvard in 1930. He was the first to describe the properties of reverse breakdown that are exploited by the zener diode. As a result, Bell Labs, where the device was developed, named the diode after him. He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

## 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.

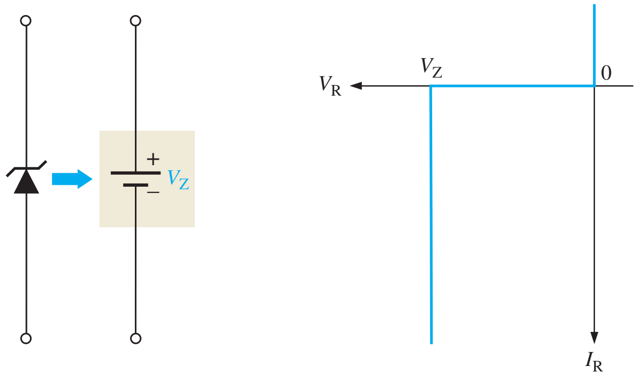


***Zener Regulation*** The ability to keep the reverse voltage across its terminals essentially constant is the key feature of the zener diode. A zener diode operating in breakdown acts as a voltage regulator because it maintains a nearly constant voltage across its terminals over a specified range of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

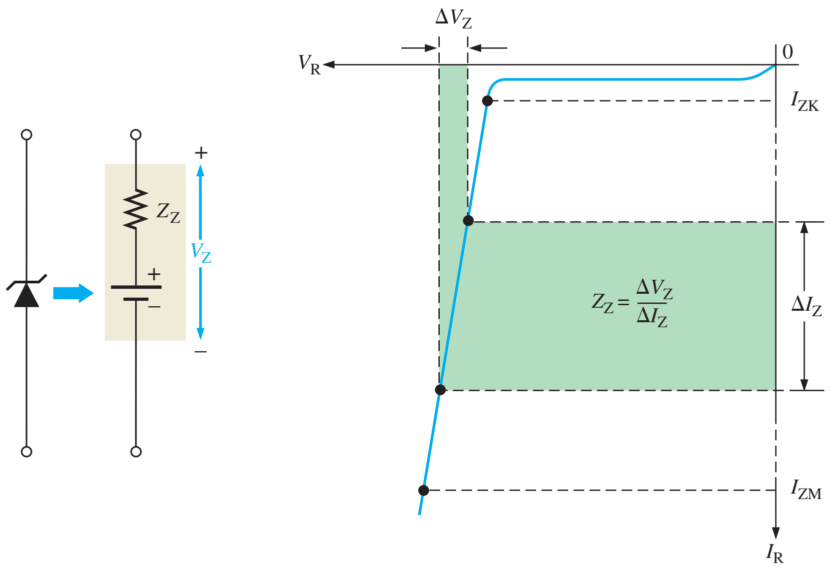
Ideal zener diode equivalent circuit model and the characteristic curve.

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 ($\Delta I_Z$) produces a small change in zener voltage ($\Delta V_Z$), as illustrated in Figure 3–5(b). By Ohm's law, the ratio of $\Delta V_Z$ to $\Delta I_Z$ 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**

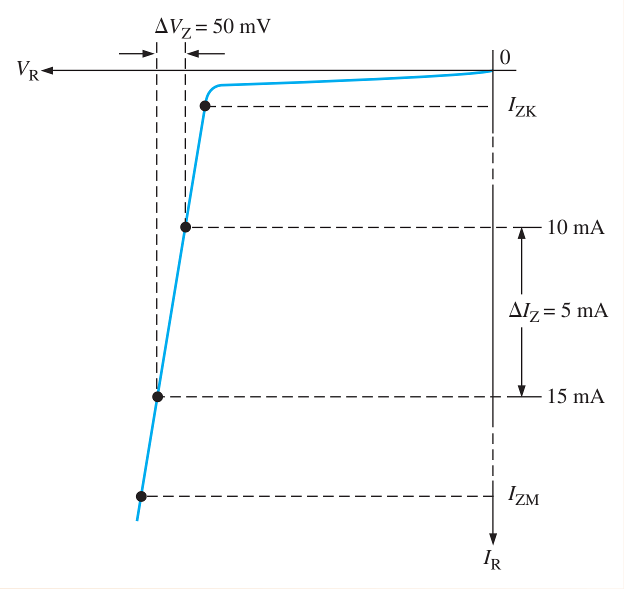
Practical zener diode equivalent circuit and the characteristic curve illustrating $Z_Z$.

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 $\Delta T$ 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, $\Delta V_Z$ 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

$$\begin{aligned}\Delta V_Z &= V_Z \times TC \times \Delta T = (8.2\text{ V})(0.05\%/^\circ\text{C})(60^\circ\text{C} - 25^\circ\text{C})\\ &= (8.2\text{ V})(0.0005/^\circ\text{C})(35^\circ\text{C}) = 144\text{ mV}\end{aligned}$$

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:

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

**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.

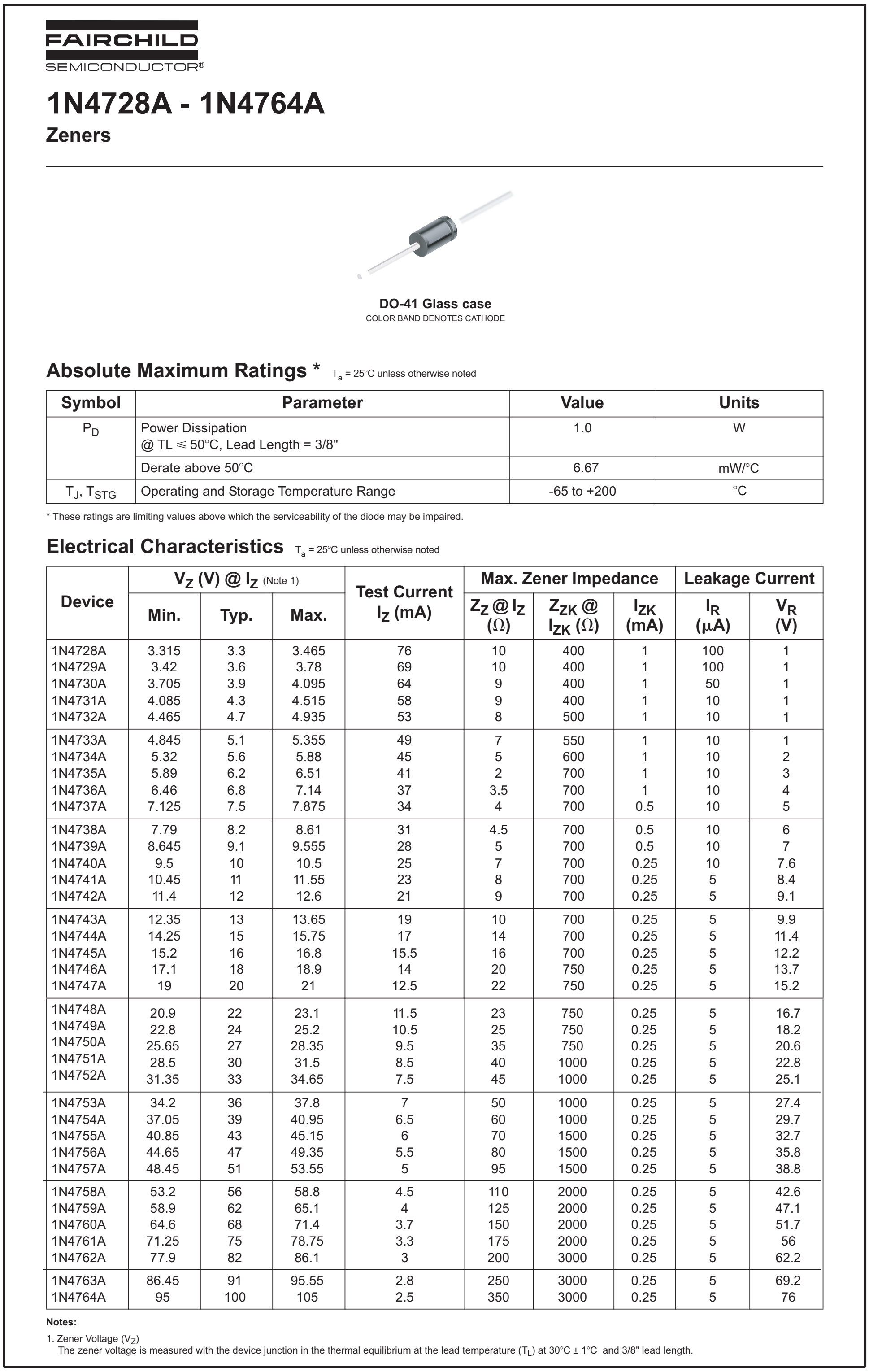
*Solution*

$$\begin{aligned}P_{D(derated)} &= P_{D(max)} - (\text{mW}/^\circ\text{C})\Delta T\\ &= 400\text{ mW} - (3.2\text{ mW}/^\circ\text{C})(90^\circ\text{C} - 50^\circ\text{C})\\ &= 400\text{ mW} - 128\text{ mW} = \mathbf{272\text{ mW}}\end{aligned}$$

*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.



FAIRCHILD
SEMICONDUCTOR®

## 1N4728A - 1N4764A

### Zeners

**DO-41 Glass case**
COLOR BAND DENOTES CATHODE

### Absolute Maximum Ratings * $T_a$ = 25°C unless otherwise noted

| Symbol | Parameter | Value | Units |
|---|---|---|---|
| $P_D$ | Power Dissipation<br>@ TL ≤ 50°C, Lead Length = 3/8" | 1.0 | W |
| | Derate above 50°C | 6.67 | mW/°C |
| $T_J$, $T_{STG}$ | Operating and Storage Temperature Range | -65 to +200 | °C |

* These ratings are limiting values above which the serviceability of the diode may be impaired.

### Electrical Characteristics $T_a$ = 25°C unless otherwise noted

| Device | $V_Z$ (V) @ $I_Z$ (Note 1) | | | Test Current $I_Z$ (mA) | Max. Zener Impedance | | | Leakage Current | |
|---|---|---|---|---|---|---|---|---|---|
| | Min. | Typ. | Max. | | $Z_Z$ @ $I_Z$ (Ω) | $Z_{ZK}$ @ $I_{ZK}$ (Ω) | $I_{ZK}$ (mA) | $I_R$ (μA) | $V_R$ (V) |
| 1N4728A | 3.315 | 3.3 | 3.465 | 76 | 10 | 400 | 1 | 100 | 1 |
| 1N4729A | 3.42 | 3.6 | 3.78 | 69 | 10 | 400 | 1 | 100 | 1 |
| 1N4730A | 3.705 | 3.9 | 4.095 | 64 | 9 | 400 | 1 | 50 | 1 |
| 1N4731A | 4.085 | 4.3 | 4.515 | 58 | 9 | 400 | 1 | 10 | 1 |
| 1N4732A | 4.465 | 4.7 | 4.935 | 53 | 8 | 500 | 1 | 10 | 1 |
| 1N4733A | 4.845 | 5.1 | 5.355 | 49 | 7 | 550 | 1 | 10 | 1 |
| 1N4734A | 5.32 | 5.6 | 5.88 | 45 | 5 | 600 | 1 | 10 | 2 |
| 1N4735A | 5.89 | 6.2 | 6.51 | 41 | 2 | 700 | 1 | 10 | 3 |
| 1N4736A | 6.46 | 6.8 | 7.14 | 37 | 3.5 | 700 | 1 | 10 | 4 |
| 1N4737A | 7.125 | 7.5 | 7.875 | 34 | 4 | 700 | 0.5 | 10 | 5 |
| 1N4738A | 7.79 | 8.2 | 8.61 | 31 | 4.5 | 700 | 0.5 | 10 | 6 |
| 1N4739A | 8.645 | 9.1 | 9.555 | 28 | 5 | 700 | 0.5 | 10 | 7 |
| 1N4740A | 9.5 | 10 | 10.5 | 25 | 7 | 700 | 0.25 | 10 | 7.6 |
| 1N4741A | 10.45 | 11 | 11.55 | 23 | 8 | 700 | 0.25 | 5 | 8.4 |
| 1N4742A | 11.4 | 12 | 12.6 | 21 | 9 | 700 | 0.25 | 5 | 9.1 |
| 1N4743A | 12.35 | 13 | 13.65 | 19 | 10 | 700 | 0.25 | 5 | 9.9 |
| 1N4744A | 14.25 | 15 | 15.75 | 17 | 14 | 700 | 0.25 | 5 | 11.4 |
| 1N4745A | 15.2 | 16 | 16.8 | 15.5 | 16 | 700 | 0.25 | 5 | 12.2 |
| 1N4746A | 17.1 | 18 | 18.9 | 14 | 20 | 750 | 0.25 | 5 | 13.7 |
| 1N4747A | 19 | 20 | 21 | 12.5 | 22 | 750 | 0.25 | 5 | 15.2 |
| 1N4748A | 20.9 | 22 | 23.1 | 11.5 | 23 | 750 | 0.25 | 5 | 16.7 |
| 1N4749A | 22.8 | 24 | 25.2 | 10.5 | 25 | 750 | 0.25 | 5 | 18.2 |
| 1N4750A | 25.65 | 27 | 28.35 | 9.5 | 35 | 750 | 0.25 | 5 | 20.6 |
| 1N4751A | 28.5 | 30 | 31.5 | 8.5 | 40 | 1000 | 0.25 | 5 | 22.8 |
| 1N4752A | 31.35 | 33 | 34.65 | 7.5 | 45 | 1000 | 0.25 | 5 | 25.1 |
| 1N4753A | 34.2 | 36 | 37.8 | 7 | 50 | 1000 | 0.25 | 5 | 27.4 |
| 1N4754A | 37.05 | 39 | 40.95 | 6.5 | 60 | 1000 | 0.25 | 5 | 29.7 |
| 1N4755A | 40.85 | 43 | 45.15 | 6 | 70 | 1500 | 0.25 | 5 | 32.7 |
| 1N4756A | 44.65 | 47 | 49.35 | 5.5 | 80 | 1500 | 0.25 | 5 | 35.8 |
| 1N4757A | 48.45 | 51 | 53.55 | 5 | 95 | 1500 | 0.25 | 5 | 38.8 |
| 1N4758A | 53.2 | 56 | 58.8 | 4.5 | 110 | 2000 | 0.25 | 5 | 42.6 |
| 1N4759A | 58.9 | 62 | 65.1 | 4 | 125 | 2000 | 0.25 | 5 | 47.1 |
| 1N4760A | 64.6 | 68 | 71.4 | 3.7 | 150 | 2000 | 0.25 | 5 | 51.7 |
| 1N4761A | 71.25 | 75 | 78.75 | 3.3 | 175 | 2000 | 0.25 | 5 | 56 |
| 1N4762A | 77.9 | 82 | 86.1 | 3 | 200 | 3000 | 0.25 | 5 | 62.2 |
| 1N4763A | 86.45 | 91 | 95.55 | 2.8 | 250 | 3000 | 0.25 | 5 | 69.2 |
| 1N4764A | 95 | 100 | 105 | 2.5 | 350 | 3000 | 0.25 | 5 | 76 |

**Notes:**

1. Zener Voltage ($V_Z$)
The zener voltage is measured with the device junction in the thermal equilibrium at the lead temperature ($T_L$) at 30°C ± 1°C and 3/8" lead length.

▲ FIGURE 3–7

Partial datasheet for the 1N4728A–1N4764A series 1 W zener diodes. Copyright Fairchild Semiconductor Corporation. Used by permission. Datasheets are available at www.fairchildsemi.com.

**Absolute Maximum Ratings** The maximum power dissipation, $P_D$, is specified as 1.0 W up to 50°C. Generally, the zener diode should be operated at least 20% below this maximum to assure reliability and longer life. The power dissipation is derated as shown on the datasheet at 6.67 mW for each degree above 50°C. For example, using the procedure illustrated in Example 3–3, the maximum power dissipation at 60°C is

$$P_D = 1\text{ W} - 10^\circ\text{C}(6.67\text{ mW}/^\circ\text{C}) = 1\text{ W} - 66.7\text{ mW} = 0.9933\text{ W}$$

At 125°C, the maximum power dissipation is

$$P_D = 1\text{ W} - 75^\circ\text{C}(6.67\text{ mW}/^\circ\text{C}) = 1\text{ W} - 500.25\text{ mW} = 0.4998\text{ W}$$

Notice that a maximum reverse current is not specified but can be determined from the maximum power dissipation for a given value of $V_Z$. For example, at 50°C, the maximum zener current for a zener voltage of 3.3 V is

$$I_{ZM} = \frac{P_D}{V_Z} = \frac{1\text{ W}}{3.3\text{ V}} = 303\text{ mA}$$

The operating junction temperature, $T_J$, and the storage temperature, $T_{STG}$, have a range of from −65°C to 200°C.

**Electrical Characteristics** The first column in the datasheet lists the zener type numbers, 1N4728A through 1N4764A.

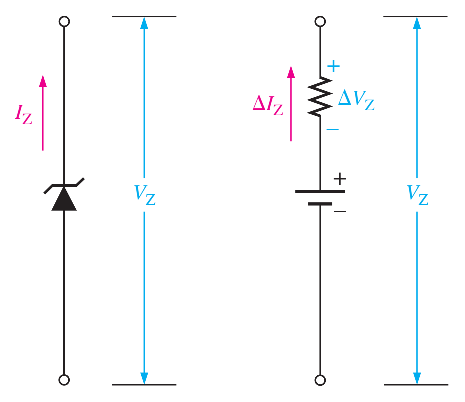
**Zener voltage, $V_Z$, and zener test current, $I_Z$** For each device type, the minimum, typical, and maximum zener voltages are listed. $V_Z$ is measured at the specified zener test current, $I_Z$. For example, the zener voltage for a 1N4728A can range from 3.315 V to 3.465 V with a typical value of 3.3 V at a test current of 76 mA.

**Maximum zener impedance** $Z_Z$ is the maximum zener impedance at the specified test current, $I_Z$. For example, for a 1N4728A, $Z_Z$ is 10 Ω at 76 mA. The maximum zener impedance, $Z_{ZK}$, at the knee of the characteristic curve is specified at $I_{ZK}$, which is the current at the knee of the curve. For example, $Z_{ZK}$ is 400 Ω at 1 mA for a 1N4728A.

**Leakage current** Reverse leakage current is specified for a reverse voltage that is less than the knee voltage. This means that the zener is not in reverse breakdown for these measurements. For example $I_R$ is 100 μA for a reverse voltage of 1 V in a 1N4728A.

**EXAMPLE 3–4**

From the datasheet in Figure 3–7, a 1N4736A zener diode has a $Z_Z$ of 3.5 Ω. The datasheet gives $V_Z = 6.8$ V at a test current, $I_Z$, of 37 mA. What is the voltage across the zener terminals when the current is 50 mA? When the current is 25 mA? Figure 3–8 represents the zener diode.



▲ FIGURE 3–8

*Solution* For $I_Z = 50$ mA: The 50 mA current is a 13 mA increase above the test current, $I_Z$, of 37 mA.

$$\Delta I_Z = I_Z - 37\text{ mA} = 50\text{ mA} - 37\text{ mA} = +13\text{ mA}$$
$$\Delta V_Z = \Delta I_Z Z_Z = (13\text{ mA})(3.5\ \Omega) = +45.5\text{ mV}$$

The change in voltage due to the increase in current above the $I_Z$ value causes the zener terminal voltage to increase. The zener voltage for $I_Z = 50$ mA is

$$V_Z = 6.8\text{ V} + \Delta V_Z = 6.8\text{ V} + 45.5\text{ mV} = \mathbf{6.85\ V}$$

For $I_Z = 25$ mA: The 25 mA current is a 12 mA decrease below the test current, $I_Z$, of 37 mA.

$$\Delta I_Z = -12\text{ mA}$$
$$\Delta V_Z = \Delta I_Z Z_Z = (-12\text{ mA})(3.5\ \Omega) = -42\text{ mV}$$

The change in voltage due to the decrease in current below the test current causes the zener terminal voltage to decrease. The zener voltage for $I_Z = 25$ mA is

$$V_Z = 6.8\text{ V} - \Delta V_Z = 6.8\text{ V} - 42\text{ mV} = \mathbf{6.76\ V}$$

*Related Problem* Repeat the analysis for $I_Z = 10$ mA and for $I_Z = 30$ mA using a 1N4742A zener with $V_Z = 12$ V at $I_Z = 21$ mA and $Z_Z = 9\ \Omega$.

**SECTION 3–1 CHECKUP**

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

1. In what region of their characteristic curve are zener diodes operated?
2. At what value of zener current is the zener voltage normally specified?
3. How does the zener impedance affect the voltage across the terminals of the device?
4. What does a positive temperature coefficient of **0.05%/°C** mean?
5. Explain power derating.

## 3–2 ZENER DIODE APPLICATIONS

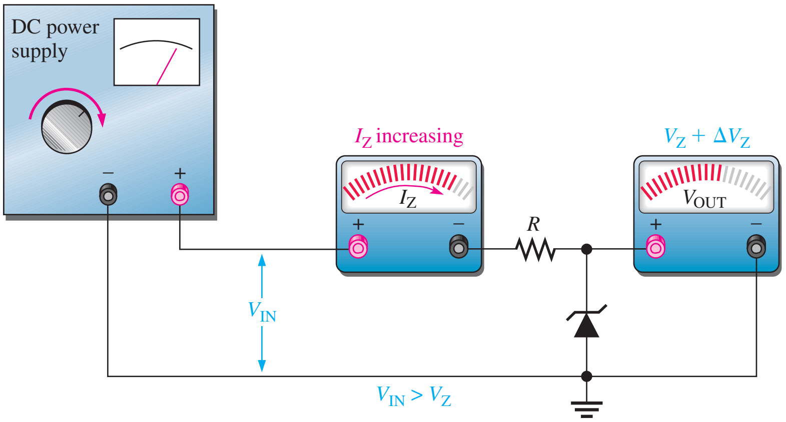
The zener diode can be used as a type of voltage regulator for providing stable reference voltages. In this section, you will see how zeners can be used as voltage references, regulators, and as simple limiters or clippers.

After completing this section, you should be able to

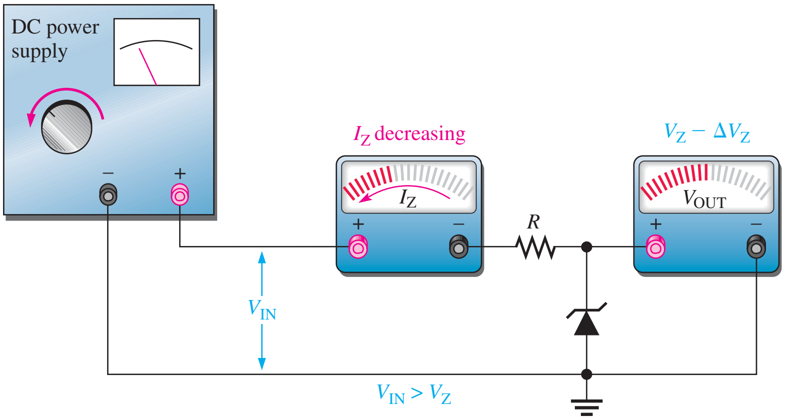
- **Apply a zener diode in voltage regulation**
- Analyze zener regulation with a variable input voltage
- Discuss zener regulation with a variable load
- Describe zener regulation from no load to full load
- Discuss zener limiting

### Zener Regulation with a Variable Input Voltage

Zener diode regulators can provide a reasonably constant dc level at the output, but they are not particularly efficient. For this reason, they are limited to applications that require only low current to the load. Figure 3–9 illustrates how a zener diode can be used to regulate a dc



(a) As the input voltage increases, the output voltage remains nearly constant ($I_{ZK} < I_Z < I_{ZM}$).



(b) As the input voltage decreases, the output voltage remains nearly constant ($I_{ZK} < I_Z < I_{ZM}$).

**FIGURE 3–9**

Zener regulation of a varying input voltage.

voltage. As the input voltage varies (within limits), the zener diode maintains a nearly constant output voltage across its terminals. However, as $V_{IN}$ changes, $I_Z$ will change proportionally so that the limitations on the input voltage variation are set by the minimum and maximum current values ($I_{ZK}$ and $I_{ZM}$) with which the zener can operate. Resistor $R$ is the series current-limiting resistor. The meters indicate the relative values and trends.

To illustrate regulation, let's use the ideal model of the 1N4740A zener diode (ignoring the zener resistance) in the circuit of Figure 3–10. The absolute lowest current that will maintain regulation is specified at $I_{ZK}$, which for the 1N4740A is 0.25 mA and represents the no-load current. The maximum current is not given on the datasheet but can be calculated from the power specification of 1 W, which is given on the datasheet. Keep in mind that both the minimum and maximum values are at the operating extremes and represent worst-case operation.

$$I_{ZM} = \frac{P_{D(max)}}{V_Z} = \frac{1\text{ W}}{10\text{ V}} = 100\text{ mA}$$

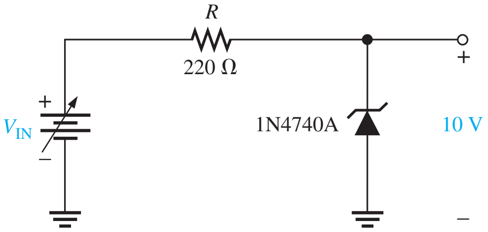


**FIGURE 3–10**

For the minimum zener current, the voltage across the 220 Ω resistor is

$$V_R = I_{ZK}R = (0.25\text{ mA})(220\ \Omega) = 55\text{ mV}$$

Since $V_R = V_{IN} - V_Z$,

$$V_{IN(min)} = V_R + V_Z = 55\text{ mV} + 10\text{ V} = 10.055\text{ V}$$

For the maximum zener current, the voltage across the 220 Ω resistor is

$$V_R = I_{ZM}R = (100\text{ mA})(220\ \Omega) = 22\text{ V}$$

Therefore,

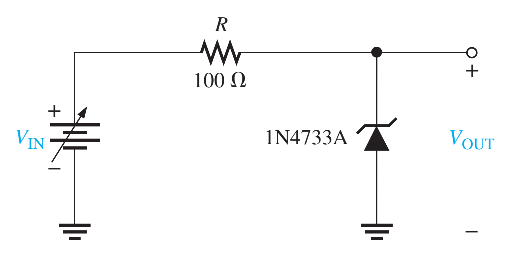
$$V_{IN(max)} = 22\text{ V} + 10\text{ V} = 32\text{ V}$$

This shows that this zener diode can ideally regulate an input voltage from 10.055 V to 32 V and maintain an approximate 10 V output. The output will vary slightly because of the zener impedance, which has been neglected in these calculations.

## EXAMPLE 3–5

Determine the minimum and the maximum input voltages that can be regulated by the zener diode in Figure 3–11.

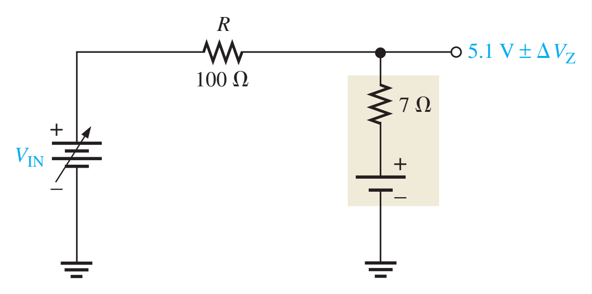
▶ FIGURE 3–11



*Solution* From the datasheet in Figure 3–7 for the 1N4733A: $V_Z = 5.1$ V at $I_Z = 49$ mA, $I_{ZK} = 1$ mA, and $Z_Z = 7\ \Omega$ at $I_Z$. For simplicity, assume this value of $Z_Z$ over the range of current values. The equivalent circuit is shown in Figure 3–12.

▶ FIGURE 3–12

Equivalent of circuit in Figure 3–11.



At $I_{ZK} = 1$ mA, the output voltage is

$$V_{OUT} \cong 5.1\text{ V} - \Delta V_Z = 5.1\text{ V} - (I_Z - I_{ZK})Z_Z = 5.1\text{ V} - (49\text{ mA} - 1\text{ mA})(7\ \Omega)$$
$$= 5.1\text{ V} - (48\text{ mA})(7\ \Omega) = 5.1\text{ V} - 0.336\text{ V} = 4.76\text{ V}$$

Therefore,

$$V_{IN(min)} = I_{ZK}R + V_{OUT} = (1\text{ mA})(100\ \Omega) + 4.76\text{ V} = \mathbf{4.86\ V}$$

To find the maximum input voltage, first calculate the maximum zener current. Assume the temperature is 50°C or below; so from Figure 3–7, the power dissipation is 1 W.

$$I_{ZM} = \frac{P_{D(max)}}{V_Z} = \frac{1\text{ W}}{5.1\text{ V}} = 196\text{ mA}$$

At $I_{ZM}$, the output voltage is

$$V_{OUT} \cong 5.1\text{ V} + \Delta V_Z = 5.1\text{ V} + (I_{ZM} - I_Z)Z_Z$$
$$= 5.1\text{ V} + (147\text{ mA})(7\ \Omega) = 5.1\text{ V} + 1.03\text{ V} = 6.13\text{ V}$$

Therefore,

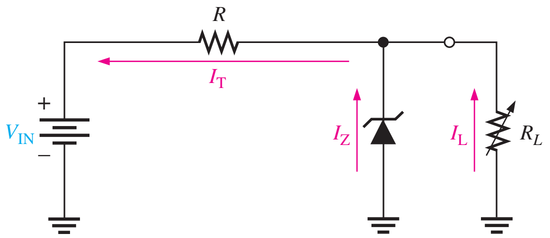
$$V_{IN(max)} = I_{ZM}R + V_{OUT} = (196\text{ mA})(100\ \Omega) + 6.13\text{ V} = \mathbf{25.7\text{ V}}$$

**Related Problem** Determine the minimum and maximum input voltages that can be regulated if a 1N4736A zener diode is used in Figure 3–11.

Open the Multisim file E03-05 in the Examples folder on the companion website. For the calculated minimum and maximum dc input voltages, measure the resulting output voltages. Compare with the calculated values.

## Zener Regulation with a Variable Load

Figure 3–13 shows a zener voltage regulator with a variable load resistor across the terminals. The zener diode maintains a nearly constant voltage across $R_L$ as long as the zener current is greater than $I_{ZK}$ and less than $I_{ZM}$.

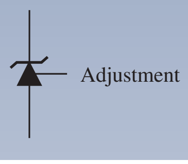


◀ FIGURE 3–13

Zener regulation with a variable load.

### FYI

One type of temperature sensor uses the zener diode breakdown voltage as a temperature indicator. The breakdown voltage of a zener is directly proportional to the Kelvin temperature. This type of sensor is small, accurate, and linear. The LM125/LM235/LM335 is an integrated circuit that is more complex than a simple zener diode. However, it displays a very precise zener characteristic. In addition to the anode and cathode terminals, this device has an adjustment for calibration purposes. The symbol is shown below.



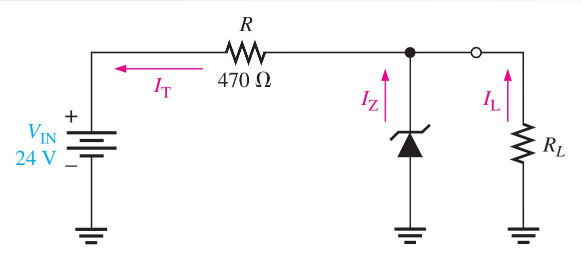
## From No Load to Full Load

When the output terminals of the zener regulator are open ($R_L = \infty$), the load current is zero and *all* of the current is through the zener; this is a no-load condition. When a load resistor ($R_L$) is connected, part of the total current is through the zener and part through $R_L$. The total current through $R$ remains essentially constant as long as the zener is regulating. As $R_L$ is decreased, the load current, $I_L$, increases and $I_Z$ decreases. The zener diode continues to regulate the voltage until $I_Z$ reaches its minimum value, $I_{ZK}$. At this point the load current is maximum, and a full-load condition exists. The following example will illustrate this.

**EXAMPLE 3–6**

Determine the minimum and the maximum load currents for which the zener diode in Figure 3–14 will maintain regulation. What is the minimum value of $R_L$ that can be used? $V_Z = 12$ V, $I_{ZK} = 1$ mA, and $I_{ZM} = 50$ mA. Assume an ideal zener diode where $Z_Z = 0\ \Omega$ and $V_Z$ remains a constant 12 V over the range of current values, for simplicity.

▶ FIGURE 3–14



**Solution** When $I_L = 0$ A ($R_L = \infty$), $I_Z$ is maximum and equal to the total circuit current $I_T$.

$$I_{Z(max)} = I_T = \frac{V_{IN} - V_Z}{R} = \frac{24\text{ V} - 12\text{ V}}{470\ \Omega} = 25.5\text{ mA}$$

If $R_L$ is removed from the circuit, the load current is 0 A. Since $I_{Z(max)}$ is less than $I_{ZM}$, 0 A is an acceptable minimum value for $I_L$ because the zener can handle all of the 25.5 mA.

$$I_{L(min)} = \mathbf{0\ A}$$

The maximum value of $I_L$ occurs when $I_Z$ is minimum ($I_Z = I_{ZK}$), so

$$I_{L(max)} = I_T - I_{ZK} = 25.5\text{ mA} - 1\text{ mA} = \mathbf{24.5\ mA}$$

The minimum value of $R_L$ is

$$R_{L(min)} = \frac{V_Z}{I_{L(max)}} = \frac{12\text{ V}}{24.5\text{ mA}} = \mathbf{490\ \Omega}$$

Therefore, if $R_L$ is less than 490 Ω, $R_L$ will draw more of the total current away from the zener and $I_Z$ will be reduced below $I_{ZK}$. This will cause the zener to lose regulation. Regulation is maintained for any value of $R_L$ between 490 Ω and infinity.

**Related Problem** Find the minimum and maximum load currents for which the circuit in Figure 3–14 will maintain regulation. Determine the minimum value of $R_L$ that can be used. $V_Z = 3.3$ V (constant), $I_{ZK} = 1$ mA, and $I_{ZM} = 150$ mA. Assume an ideal zener.

Open the Multisim file E03-06 in the Examples folder on the companion website. For the calculated minimum value of load resistance, verify that regulation occurs.

In the last example, we assumed that $Z_Z$ was zero and, therefore, the zener voltage remained constant over the range of currents. We made this assumption to demonstrate the concept of how the regulator works with a varying load. Such an assumption is often acceptable and in many cases produces results that are reasonably accurate. In Example 3–7, we will take the zener impedance into account.

## EXAMPLE 3–7

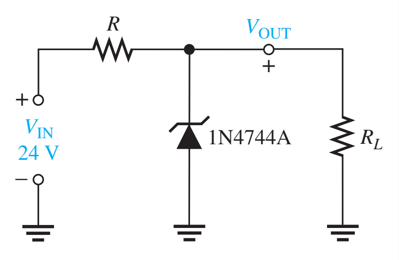
For the circuit in Figure 3–15:

**(a)** Determine $V_{OUT}$ at $I_{ZK}$ and at $I_{ZM}$.

**(b)** Calculate the value of $R$ that should be used.

**(c)** Determine the minimum value of $R_L$ that can be used.

▶ FIGURE 3–15



*Solution* The 1N4744A zener used in the regulator circuit of Figure 3–15 is a 15 V diode. The datasheet in Figure 3–7 gives the following information:
$V_Z = 15\text{ V} @ I_Z = 17\text{ mA}, I_{ZK} = 0.25\text{ mA}$, and $Z_Z = 14\ \Omega$.

**(a)** For $I_{ZK}$:

$$V_{OUT} = V_Z - \Delta I_Z Z_Z = 15\text{ V} - \Delta I_Z Z_Z = 15\text{ V} - (I_Z - I_{ZK})Z_Z$$
$$= 15\text{ V} - (16.75\text{ mA})(14\ \Omega) = 15\text{ V} - 0.235\text{ V} = \mathbf{14.76\text{ V}}$$

Calculate the zener maximum current. The maximum power dissipation is 1 W.

$$I_{ZM} = \frac{P_{D(max)}}{V_Z} = \frac{1\text{ W}}{15\text{ V}} = 66.7\text{ mA}$$

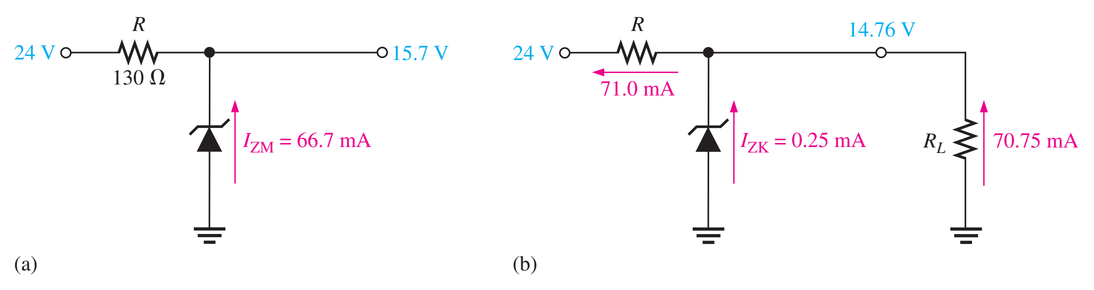
For $I_{ZM}$:

$$V_{OUT} = V_Z + \Delta I_Z Z_Z = 15\text{ V} + \Delta I_Z Z_Z$$
$$= 15\text{ V} + (I_{ZM} - I_Z)Z_Z = 15\text{ V} + (49.7\text{ mA})(14\ \Omega) = \mathbf{15.7\text{ V}}$$

**(b)** Calculate the value of $R$ for the maximum zener current that occurs when there is no load as shown in Figure 3–16(a).

$$R = \frac{V_{IN} - V_{OUT}}{I_{ZK}} = \frac{24\text{ V} - 15.7\text{ V}}{66.7\text{ mA}} = 124\ \Omega$$

$R = \mathbf{130\ \Omega}$ (nearest larger standard value).



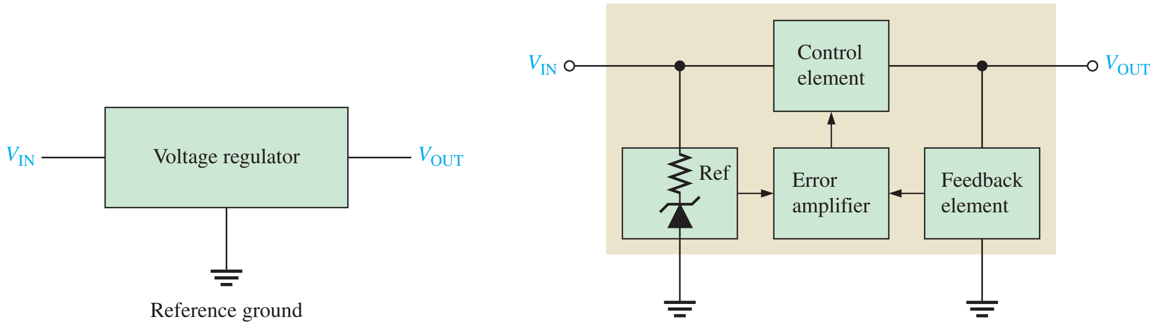
▲ FIGURE 3–16

**(c)** For the minimum load resistance (maximum load current), the zener current is minimum ($I_{ZK} = 0.25$ mA) as shown in Figure 3–16(b).

$$I_T = \frac{V_{IN} - V_{OUT}}{R} = \frac{24\text{ V} - 14.76\text{ V}}{130\ \Omega} = 71.0\text{ mA}$$
$$I_L = I_T - I_{ZK} = 71.0\text{ mA} - 0.25\text{ mA} = 70.75\text{ mA}$$
$$R_{L(min)} = \frac{V_{OUT}}{I_L} = \frac{14.76\text{ V}}{70.75\text{ mA}} = \mathbf{209\ \Omega}$$

*Related Problem* Repeat each part of the preceding analysis if the zener is changed to a 1N4742A 12 V device.

You have seen how the zener diode regulates voltage. Its regulating ability is somewhat limited by the change in zener voltage over a range of current values, which restricts the load current that it can handle. To achieve better regulation and provide for greater variations in load current, the zener diode is combined as a key element with other circuit components to create a 3-terminal linear voltage regulator. Three-terminal voltage regulators that were introduced in Chapter 2 are IC devices that use the zener to provide a reference voltage for an internal amplifier. For a given dc input voltage, the 3-terminal regulator maintains an essentially constant dc voltage over a range of input voltages and load currents. The dc output voltage is always less than the input voltage. The details of this type of regulator are covered in Chapter 17. Figure 3–17 illustrates a basic 3-terminal regulator showing where the zener diode is used.



(a) Symbol

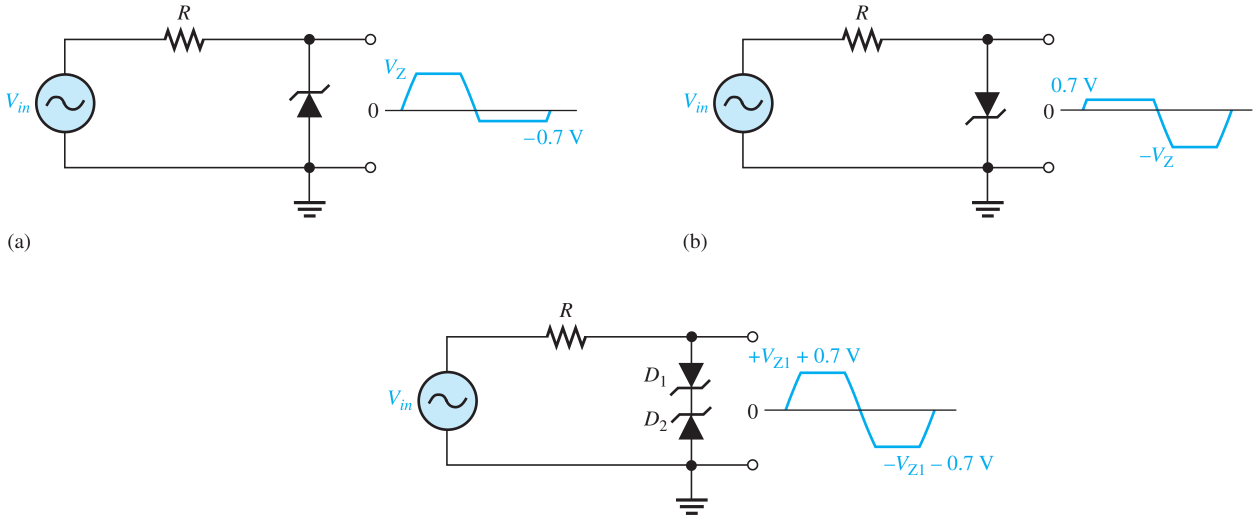
(b) Block diagram

▲ FIGURE 3–17

Three-terminal voltage regulators.

## Zener Limiter

In addition to voltage regulation applications, zener diodes can be used in ac applications to limit voltage swings to desired levels. Figure 3–18 shows three basic ways the limiting action of a zener diode can be used. Part (a) shows a zener used to limit the positive peak of a signal voltage to the selected zener voltage. During the negative alternation, the zener acts as a forward-biased diode and limits the negative voltage to −0.7 V. When the zener



(a)

(b)

(c)

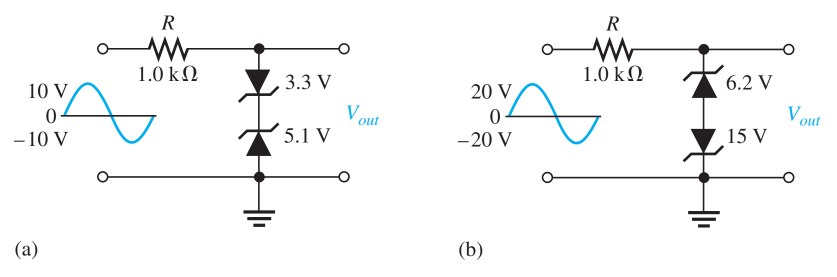
▲ FIGURE 3–18

Basic zener limiting action with a sinusoidal input voltage.

is turned around, as in part (b), the negative peak is limited by zener action and the positive voltage is limited to +0.7 V. Two back-to-back zeners limit both peaks to the zener voltage ±0.7 V, as shown in part (c). During the positive alternation, $D_2$ is functioning as the zener limiter and $D_1$ is functioning as a forward-biased diode. During the negative alternation, the roles are reversed.

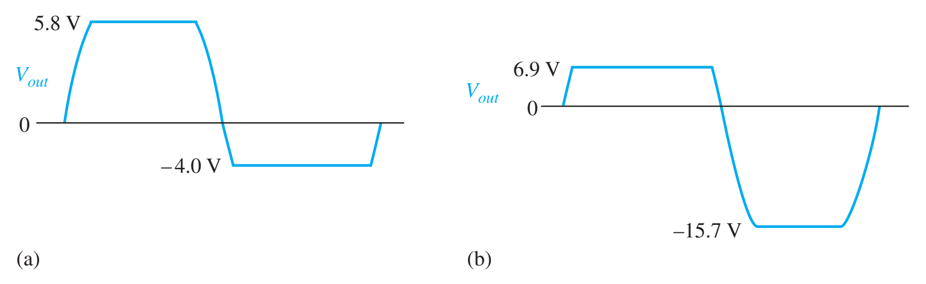
### EXAMPLE 3–8

Determine the output voltage for each zener limiting circuit in Figure 3–19.



▲ FIGURE 3–19

**Solution** See Figure 3–20 for the resulting output voltages. Remember, when one zener is operating in breakdown, the other one is forward-biased with approximately 0.7 V across it.



▲ FIGURE 3–20

**Related Problem**

**(a)** What is the output in Figure 3–19(a) if the input voltage is increased to a peak value of 20 V?

**(b)** What is the output in Figure 3–19(b) if the input voltage is decreased to a peak value of 5 V?

Open the Multisim file E03-08 in the Examples folder on the companion website. For the specified input voltages, measure the resulting output waveforms. Compare with the waveforms shown in the example.

### SECTION 3–2 CHECKUP

1. In a zener diode regulator, what value of load resistance results in the maximum zener current?
2. Explain the terms *no load* and *full load*.
3. How much voltage appears across a zener diode when it is forward-biased?

## 3–3 THE VARACTOR DIODE

The junction capacitance of diodes varies with the amount of reverse bias. Varactor diodes are specially designed to take advantage of this characteristic and are used as voltage-controlled capacitors rather than traditional diodes. These devices are commonly used in communication systems. Varactor diodes are also referred to as *varicaps* or *tuning diodes.*

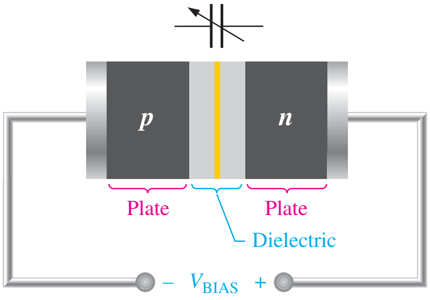
After completing this section, you should be able to

- **Describe the varactor diode characteristic and analyze its operation**
- Discuss the basic operation of a varactor
  - ◆ Explain why a reverse-biased varactor acts as a capacitor ◆ Calculate varactor capacitance ◆ Identify the varactor schematic symbol
- Interpret a varactor diode datasheet
  - ◆ Define and discuss capacitance tolerance range ◆ Define and discuss capacitance ratio ◆ Discuss the back-to-back configuration
- Discuss and analyze the application of a varactor in a resonant band-pass filter

A **varactor** is a diode that always operates in reverse bias and is doped to maximize the inherent capacitance of the depletion region. The depletion region acts as a capacitor dielectric because of its nonconductive characteristic. The *p* and *n* regions are conductive and act as the capacitor plates, as illustrated in Figure 3–21.

▶ FIGURE 3–21

The reverse-biased varactor diode acts as a variable capacitor.



### Basic Operation

Recall that capacitance is determined by the parameters of plate area ($A$), dielectric constant ($\epsilon$), and plate separation ($d$), as expressed in the following formula:

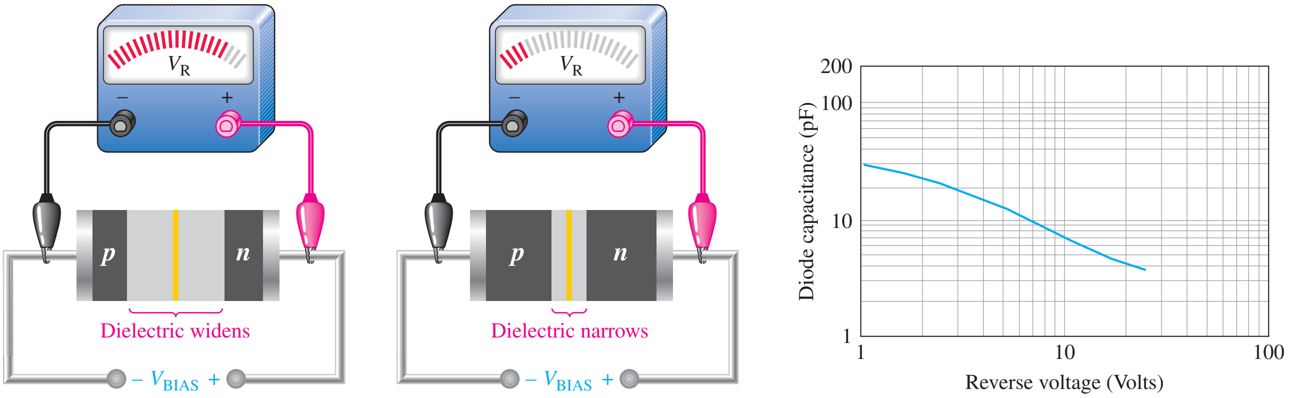
$$C = \frac{A\epsilon}{d}$$

As the reverse-bias voltage increases, the depletion region widens, effectively increasing the plate separation, thus decreasing the capacitance. When the reverse-bias voltage decreases, the depletion region narrows, thus increasing the capacitance. This action is shown in Figure 3–22(a) and (b). A graph of diode capacitance ($C_T$) versus reverse voltage for a certain varactor is shown in Figure 3–22(c). For this particular device, $C_T$ varies from 30 pF to slightly less than 4 pF as $V_R$ varies from 1 V to 30 V.

In a varactor diode, these capacitance parameters are controlled by the method of doping near the *pn* junction and the size and geometry of the diode's construction. Nominal varactor capacitances are typically available from a few picofarads to several hundred picofarads. Figure 3–23 shows a common symbol for a varactor.

▲ FIGURE 3–23

Varactor diode symbol.



(a) Greater reverse bias, less capacitance (b) Less reverse bias, greater capacitance (c) Example of a diode capacitance versus reverse voltage graph

▲ **FIGURE 3–22**

Varactor diode capacitance varies with reverse voltage.

## Varactor Datasheet Information

A partial datasheet for a specific series of varactor diode (Zetex 830 series) is shown in Figure 3–24.

***Capacitance Tolerance Range*** The minimum, nominal, and maximum values of capacitance are shown on the datasheet. For example, when reverse-biased at 3 V, the 832A can

**Tuning characteristics at $T_{amb}$ = 25°C**

| Part | Capacitance (pF) | | | Min Q<br>$V_R$ = 3V<br>f = 50MHz | Capacitance ratio<br>$C_2 / C_{20}$<br>@ f = 1MHz | |
|---|---|---|---|---|---|---|
| | Min. | Nom. | Max. | | Min. | Max. |
| 829A | 7.38 | 8.2 | 9.02 | 250 | 4.3 | 5.8 |
| 829B | 7.79 | 8.2 | 8.61 | 250 | 4.3 | 5.8 |
| 830A | 9.0 | 10.0 | 11.0 | 300 | 4.5 | 6.0 |
| 830B | 9.5 | 10.0 | 10.5 | 300 | 4.5 | 6.0 |
| 831A | 13.5 | 15.0 | 16.5 | 300 | 4.5 | 6.0 |
| 831B | 14.25 | 15.0 | 15.75 | 300 | 4.5 | 6.0 |
| 832A | 19.8 | 22.0 | 24.2 | 200 | 5.0 | 6.5 |
| 832B | 20.9 | 22.0 | 23.1 | 200 | 5.0 | 6.5 |
| 833A | 29.7 | 33.0 | 36.3 | 200 | 5.0 | 6.5 |
| 833B | 31.35 | 33.0 | 34.65 | 200 | 5.0 | 6.5 |
| 834A | 42.3 | 47.0 | 51.7 | 200 | 5.0 | 6.5 |
| 834B | 44.65 | 47.0 | 49.35 | 200 | 5.0 | 6.5 |
| 835A | 61.2 | 68.0 | 74.8 | 100 | 5.0 | 6.5 |
| 835B | 64.6 | 68.0 | 71.4 | 100 | 5.0 | 6.5 |
| 836A | 90.0 | 100.0 | 110.0 | 100 | 5.0 | 6.5 |
| 836B | 95.0 | 100.0 | 105.0 | 100 | 5.0 | 6.5 |

**Absolute maximum ratings**

| Parameter | Symbol | Max. | Unit |
|---|---|---|---|
| Forward current | $I_F$ | 200 | mA |
| Power dissipation at $T_{amb}$ = 25°C SOT23 | $P_{tot}$ | 330 | mW |
| Power dissipation at $T_{amb}$ = 25°C SOD323 | $P_{tot}$ | 330 | mW |
| Power dissipation at $T_{amb}$ = 25°C SOD523 | $P_{tot}$ | 250 | mW |
| Operating and storage temperature range | | -55 to +150 | °C |

**Electrical characteristics at $T_{amb}$ = 25°C**

| Paramater | Conditions | Min. | Typ. | Max. | Unit |
|---|---|---|---|---|---|
| Reverse breakdown voltage | $I_R$ = 10 A | 25 | | | V |
| Reverse voltage leakage | $V_R$ = 20V | | 0.2 | 20 | nA |
| Temperature coefficient of capacitance | $V_R$ = 3V, f = 1MHz | | 300 | 400 | ppCm/°C |

◀ **FIGURE 3–24**

Partial datasheet for the Zetex 830 series varactor diodes. Courtesy of Zetex Semiconductors PLC. Datasheets are available at www.datasheetcatalog/zetexsemiconductors/1/.

exhibit a capacitance anywhere between 19.8 pF and 24.2 pF. This tolerance range should not be confused with the range of capacitance values that result from varying the reverse bias as determined by the capacitance ratio.

***Capacitance Ratio*** The varactor **capacitance ratio** is also known as the *tuning ratio*. It is the ratio of the diode capacitance at a minimum reverse voltage to the diode capacitance at a maximum reverse voltage. For the varactor diodes represented in Figure 3–24, the capacitance ratio is the ratio of $C$ measured at a $V_R$ of 2 V divided by $C$ measured at a $V_R$ of 20 V. The capacitance ratio is designated as $C_2/C_{20}$ in this case.

For the 832A, the minimum capacitance ratio is 5.0. This means that the capacitance value decreases by a factor of 5.0 as $V_R$ is increased from 2 V to 20 V. The following calculation illustrates how to use the capacitance ratio ($CR$) to find the capacitance range for the 832A. If $C_2 = 22\text{ pF}$ and the minimum $CR = C_2/C_{20} = 5.0$,

$$C_{20} = \frac{C_2}{CR} = \frac{22\text{ pF}}{5} = 4.4\text{ pF}$$

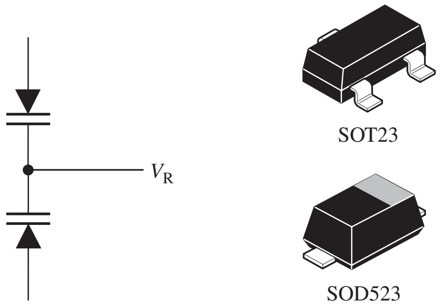
The diode capacitance varies from 22 pF to 4.4 pF when $V_R$ is increased from 2 V to 20 V.

The Zetex 830 series of varactor diodes are hyper-abrupt junction devices. The doping in the *n* and *p* regions is made uniform so that at the *pn* junction there is a very abrupt change from *n* to *p* instead of the more gradual change found in the rectifier diodes. The abruptness of the *pn* junction determines the capacitance ratio.

***Back-to-Back Configuration*** One of the drawbacks of using just a single varactor diode in certain applications, such as rf tuning, is that if the diode is forward-biased by the rf signal during part of the ac cycle, its reverse leakage will increase momentarily. Also, a type of distortion called *harmonic distortion* is produced if the varactor is alternately biased positively and negatively. To avoid harmonic distortion, you will often see two varactor diodes back to back, as shown in Figure 3–25(a) with the reverse dc voltage applied to both devices simultaneously. The two tuning diodes will be driven alternately into high and low capacitance, and the net capacitance will remain constant and is unaffected by the rf signal amplitude. The Zetex 832A varactor diode is available in a back-to-back configuration in an SOT23 package or as a single diode in an SOD523 package, as shown in Figure 3–25(b). Although the cathodes in the back-to-back configuration are connected to a common pin, each diode can also be used individually.

▶ FIGURE 3–25

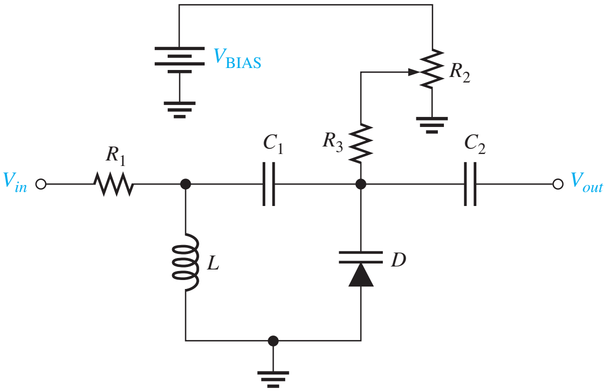
Varactor diodes and typical packages.



(a) Back-to-back configuration (b)

## An Application

A major application of varactors is in tuning circuits. For example, VHF, UHF, and satellite receivers utilize varactors. Varactors are also used in cellular communications. When used in a parallel resonant circuit, as illustrated in Figure 3–26, the varactor acts as a



◀ FIGURE 3–26

A resonant band-pass filter using a varactor diode for adjusting the resonant frequency over a specified range.

variable capacitor, thus allowing the resonant frequency to be adjusted by a variable voltage level. The varactor diode provides the total variable capacitance in the parallel resonant band-pass filter. The varactor diode and the inductor form a parallel resonant circuit from the output to ac ground. The capacitors $C_1$ and $C_2$ have no effect on the filter's frequency response because their reactances are negligible at the resonant frequencies. $C_1$ prevents a dc path from the potentiometer wiper back to the ac source through the inductor and $R_1$. $C_2$ prevents a dc path from the wiper of the potentiometer to a load on the output. The potentiometer $R_2$ forms a variable dc voltage for biasing the varactor. The reverse-bias voltage across the varactor can be varied with the potentiometer.

Recall that the parallel resonant frequency is

$$f_r \cong \frac{1}{2\pi\sqrt{LC}}$$

**EXAMPLE 3–8**

**(a)** Given that the capacitance of a Zetex 832A varactor is approximately 40 pF at 0 V bias and that the capacitance at a 2 V reverse bias is 22 pF, determine the capacitance at a reverse bias of 20 V using the specified minimum capacitance ratio.

**(b)** Using the capacitances at bias voltages of 0 V and 20 V, calculate the resonant frequencies at the bias extremes for the circuit in Figure 3–26 if $L = 2$ mH.

**(c)** Verify the frequency calculations by simulating the circuit in Figure 3–26 for the following component values: $R_1 = 47\text{ k}\Omega$, $R_2 = 10\text{ k}\Omega$, $R_3 = 5.1\text{ M}\Omega$, $C_1 = 10\text{ nF}$, $C_2 = 10\text{ nF}$, $L = 2\text{ mH}$, and $V_{BIAS} = 20\text{ V}$.

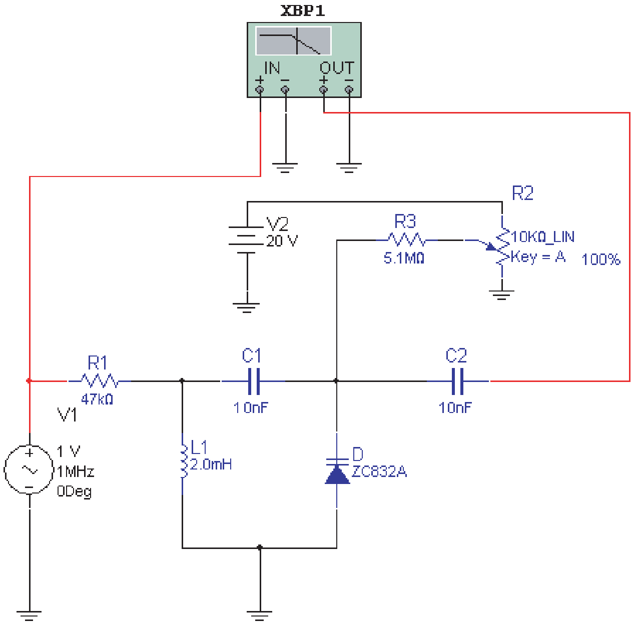
*Solution*

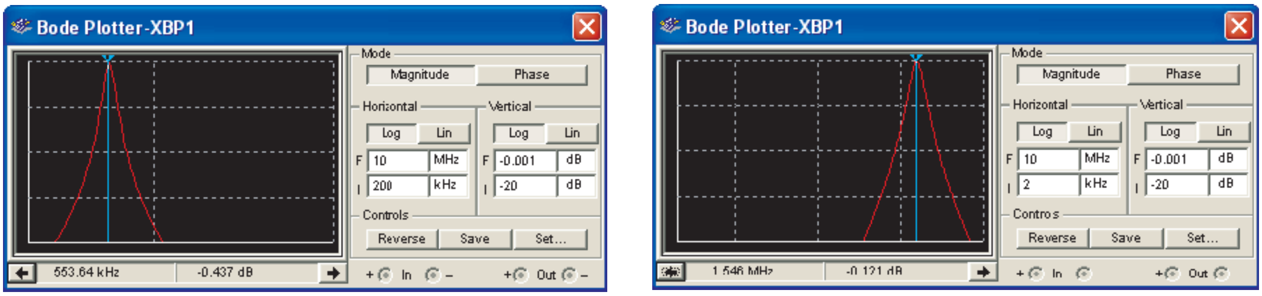
**(a)** $C_{20} = \dfrac{C_2}{CR} = \dfrac{22\text{ pF}}{5.0} = \mathbf{4.4\ pF}$

**(b)** $f_0 = \dfrac{1}{2\pi\sqrt{LC}} = \dfrac{1}{2\pi\sqrt{(2\text{ mH})(40\text{ pF})}} = \mathbf{563\ kHz}$

$$f_{20} = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{(2\text{ mH})(4.4\text{ pF})}} = \mathbf{1.7\ MHz}$$

**(c)** The Multsim simulation of the circuit is shown in Figure 3–27. The Bode plotters show the frequency responses at 0 V and 20 V reverse bias. The center of the 0 V bias response curve is at 553.64 kHz and the center of the 20 V bias response curve is at 1.548 MHz. These results agree reasonably well with the calculated values.





Horizontal: Log, F 10 MHz, I 200 kHz; Vertical: Log, F -0.001 dB, I -20 dB

553.64 kHz -0.437 dB

Frequency response for 0 V varactor bias

Horizontal: Log, F 10 MHz, I 2 kHz; Vertical: Log, F -0.001 dB, I -20 dB

1.546 MHz -0.121 dB

Frequency response for 20 V reverse varactor bias

▲ **FIGURE 3–27**

Multisim simulation.

These results show that this circuit can be tuned over most of the AM broadcast band.

*Related Problem* How could you increase the tuning range of the circuit?

**SECTION 3–3 CHECKUP**

1. What is the key feature of a varactor diode?
2. Under what bias condition is a varactor operated?
3. What part of the varactor produces the capacitance?
4. Based on the graph in Figure 3–22(c), what happens to the diode capacitance when the reverse voltage is increased?
5. Define *capacitance ratio*.