series resistor to regulate an input of between 10 and 15 V down to approximately 5 V over a current range from 0 to 45 mA.

Aside from selecting a diode with the appropriate Zener voltage, a diode and resistor combination must be selected that can properly handle the circuit's worst-case power dissipation. Many types of regulators, including this one, operate by converting excess power into heat. The resistor is chosen to be as large as possible to minimize power dissipation while maintaining sufficient current through the diode to establish the desired voltage. In this situation, the resistor is bounded at a maximum value by its voltage drop at the maximum load current with a minimum input voltage, 10 V. The voltage drop in this situation is 4.9 V at 45 mA. 100 Ω is chosen, because it is smaller than the calculated value of 108 Ω, thereby providing a guaranteed minimum excess current for the diode to remain active: 4 mA. The circuit must allow the diode to conduct sufficient current at all times to remain active. Otherwise, the diode may take too long to begin conducting when the load current drops, thereby allowing V_{OUT} to exceed its specified range. The 1N4733A is characterized with Zener "knee" currents down to 1 mA, sufficiently below our 4-mA design point to remain active.*

Under this most favorable circumstance of minimum input voltage and maximum load current, the resistor and diode dissipate a minimum of 240 mW and 20 mW, respectively, for a total of just over a 0.25 W. If the input remains at 10 V, but the load current drops to its minimum value, 0 mA, the diode must shunt the full current to ground, resulting in 250 mW dissipated by the diode.

As the input voltage rises to its maximum of 15 V, the regulator must convert more power into heat. Now, the resistor must drop 9.9 V, burning 980 mW. This results in a current through the resistor of 100 mA, but the load is drawing only a maximum of 45 mA. Therefore, the diode must shunt the difference, 55 mA, to ground, thereby dissipating 280 mW. Unfortunately, this is not the worst-case scenario. The load is rated at a minimum current of zero, meaning that the diode must be able to shunt the full 100 mA that flows through the resistor when the input is at its maximum. This equates to a maximum diode power dissipation of 510 mW and an overall worst-case power dissipation for the regulator of nearly 1.5 W.

After calculating the maximum operating conditions of the regulator components, we must verify that they are within the manufacturers' specifications. The resistor dissipates nearly 1 W. Finding a resistor that can safely dissipate this quantity of power is fairly easy: a 2- or 3-W power resistor can be chosen. For the diode, a check of the data sheet confirms that the maximum current through the diode, 100 mA, is within the manufacturer's specifications of a continuous Zener (reverse bias) current of 178 mA.†

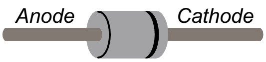

FIGURE 17.6 DO-41 package.

Next, we must ensure that the diode can handle 510 mW of continuous power dissipation at the circuit's maximum ambient air operating temperature, $T_{A(MAX)}$, which we will assume to be 40°C. The 1N4733A, manufactured in the axial-leaded DO-41 package shown in Fig. 17.6, has several relevant specifications:‡

- $P_{D(MAX)}$ = 1 W at 50°C, derate at 6.67 mW/°C above 50°C
- $T_{J(MAX)}$ = 200°C
- θ_{JA} = 100°C/W

According to the first specification, $P_{D(MAX)}$, we are operating safely. The power is approximately half the rated value, and $T_{A(MAX)}$ is under 50°C. Because the manufacturer also provides θ_{JA}, we can

* Zeners 1N4728A-1N4752A, Fairchild Semiconductor, 2001, p. 1.
† *Ibid.*
‡ *Ibid.*

perform a calculation to estimate how much margin we have. Recall that $T_J = T_A + \theta_{JA}P_D$. Therefore, $T_{J(MAX)} = T_{A(MAX)} + \theta_{JA}P_{D(MAX)} = 40°C + 100°C/W \times 0.51\ W = 91°C$. which is less than half the rated maximum.

Observe that if the junction temperature calculation used 1 W instead of 0.51 W and 50°C instead of 40°C, $T_{J(MAX)}$ would be calculated at just 150°C, well under the 200°C specification. This would ordinarily indicate that the device could handle more power at this temperature, yet the $P_{D(MAX)}$ specification disallows more power. Inherent limitations of a semiconductor may be more restrictive than the basic thermal resistance calculations would otherwise indicate. For this reason, it is important to look at all of the published specifications as a whole instead of relying on just a subset when determining the safe operating conditions for a semiconductor.

The shunt Zener regulator is fairly simple to construct but, aside from loose regulation accuracy, it also has the disadvantage that constant current is drawn from the input supply regardless of how much current the load is drawing. The diode establishes a fixed V_{OUT}, which results in a fixed current across the series resistor. In situations in which the V_{IN}/V_{OUT} differential is lower and the load current is specified over a smaller range, this type of regulator can be very useful—particularly at higher voltages for which other types of regulators get more complex. This narrower operating range enables a more efficient circuit design, because the series resistor dissipates less power by virtue of the lower voltage difference, and the diode dissipates less power because it has a narrower range of current slack for which it has to compensate when the load current falls to its minimum value.

17.4 TRANSISTORS AND DISCRETE SERIES REGULATORS

A significant inefficiency of the shunt regulator is that it must consume current that is not required by the load so as to maintain a fixed output voltage. Transistors can largely overcome this problem when used instead of a dropping resistor. Unlike a resistor that requires a current in proportion to the desired voltage drop, a BJT's collector-emitter voltage can be arbitrarily large without a proportional current flow. Consider the circuit in Fig. 17.7 with the same input/output ranges as the previous shunt regulator example, but using the TIP31 NPN power transistor as the series, or pass, element.

V_{OUT} is fixed by the transistor's base voltage less its V_{BE}, and the base voltage is fixed by a Zener diode reference of 5.6 V using a 1N4734A. Assuming $V_{BE} = 0.7$ V, $V_{OUT} \approx 4.9$ V. With the collector floating with changing V_{IN}, the input/output differential is taken up by V_{CE} without any proportional current requirement. The power dissipated by the pass transistor is dominated by $V_{CE} \times I_{OUT}$. Therefore, for constant V_{CE}, the transistor dissipates less power under light load conditions and more

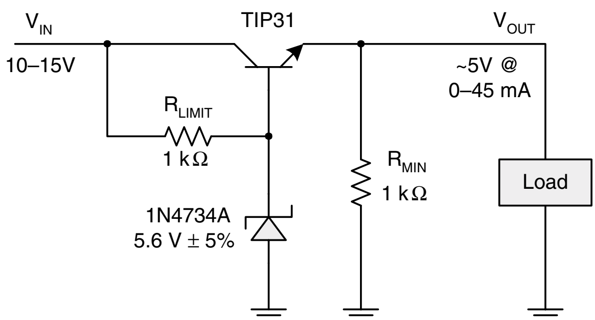

FIGURE 17.7 NPN series regulator.