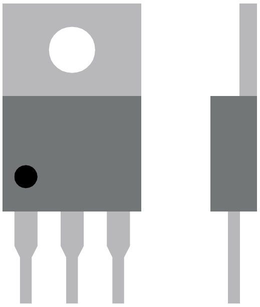

FIGURE 17.3 TO-220 package.

As an example, consider a device housed in a TO-220 package, shown in Fig. 17.3, with θ_{JA} = 65°C/W. The TO-220 is a common three-leaded package for power semiconductors including diodes, transistors, and integrated voltage regulators. If $T_{J(MAX)}$ = 150°C and $T_{A(MAX)}$ = 40°C, there is a 110°C temperature rise budget that corresponds to $P_D = \Delta T \div \theta_{JA} = 1.6$ W (always round down for safety when dealing with thermal and power limits). If 1.6 W is insufficient for the application, there are several choices. The best option is to reduce power consumption so that heat is less of a problem in the first place. However, this is often not possible, given the design constraints. Failing that, either a larger package with lower θ_{JA} can be chosen, or the TO-220 can be attached to a heat sink to decrease the overall θ_{JA}. The TO-220 has a mounting hole to facilitate heat sink attachment.

Heat sinks are very common, because packages have practical limitations on how low their θ_{JA} can be. Thermal resistance is a function of materials and surface area. A small package has limited surface area. A good heat sink is constructed of a material that has low thermal resistance (most commonly, aluminum or copper) and that has a large surface area to radiate heat into the air. When a heat sink is attached, the device's θ_{JA} becomes irrelevant, and θ_{JC} becomes important, because it is the thermal resistance through the package to another material that matters. A TO-220's typical θ_{JC} is just 2.5°C/W—more than an order of magnitude better than θ_{JA}—because thermal conduction between attached metal surfaces is far better than between metal and air.

With a heat sink attached to the package, the heat sink's θ becomes relevant. Heat sinks are available in a wide range of sizes according to how much power needs to be dissipated. Off-the-shelf heat sinks for TO-220 packages can be found with thermal resistances under 3°C/W in still air. The junction between the heat sink and the IC package adds its own thermal resistance, which is often minimized via the application of thermally conductive grease. Assuming $\theta_{HEATSINK}$ = 3°C/W, the total θ_{JA} is now just 2.5 + 3 = 5.5°C/W. From a strictly thermal perspective, the device can now safely dissipate 110°C ÷ θ_{TOTAL} = 20 W! This solves the heating problem, but does not automatically mean that the semiconductor can handle this much power even when adequately cooled. Be sure to check the device's inherent current and voltage ratings to see if they become the limiting factor when heat is accommodated.

Semiconductors intended for lower-power applications do not always have associated thermal resistance specifications. Instead, they are rated for a certain power dissipation at a given ambient temperature, often 25°C—room temperature. If the ambient temperature exceeds the rating, a power derating curve or coefficient is provided that can be used to determine the safe power dissipation at a specific temperature. For example, a device may be rated for 400 mW at T_A = 25°C with a derating coefficient of 3.2 mW/°C. This means that, if the actual maximum T_A is 40°C, the device's power rating is reduced by $\Delta T_A \times 3.2$ mW/°C = 15°C × 3.2 mW/°C = 48 mW, for an overall rating of just 352 mA.

It pays to be conservative when designing power regulation circuits, both in terms of current/voltage headroom as well as thermal headroom. The life span of most components is reduced as temperatures rise, so a cooler product is a more reliable product.

17.3 ZENER DIODES AND SHUNT REGULATORS

Perhaps the simplest type of voltage regulator is one formed by using a diode in a shunt circuit. A shunt regulator, shown in Fig. 17.4, consists of a device that conducts excess current to ground to maintain a fixed voltage between its two terminals. A series resistor, R_{DROP}, serves as the voltage-

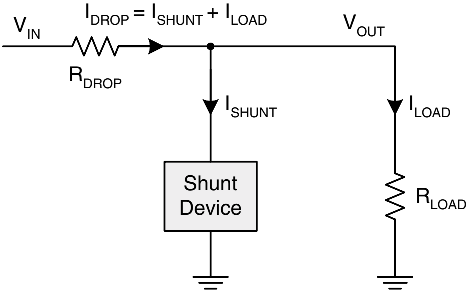

FIGURE 17.4 General shunt regulator.

dropping element. (The shunt device is typically a diode but can also be a more complex circuit that exhibits better characteristics.) When the load current increases, the shunt device draws less current to maintain the same V_{OUT}. The shunt device cannot feed current into the circuit, placing an upper limit on I_{LOAD} beyond which V_{OUT} will drop out of regulation. This concept was already touched on when diodes were discussed in an earlier chapter in the context of forming a voltage reference. A voltage reference may be a shunt regulator, and it is usually called upon to supply very minimal current.

Ordinary diodes do not make very practical shunt regulators, because their forward voltages are relatively small (0.3 to 0.7 V). Diodes are normally operated under forward bias conditions, but they can be made to conduct under reverse bias if the applied voltage exceeds their reverse breakdown voltage. Zener diodes are specifically designed to operate safely at their reverse breakdown voltage—the Zener voltage, V_Z. Furthermore, Zener diodes are manufactured with a wide range of voltages so that they can serve as shunt regulators or references. The common range of V_Z is from 2.4 to 33 V, with a typical tolerance of 5 percent, in increments of approximately 0.3 V at the low end, 1 V in the middle, and 3 V at the upper end of the range. Beyond their specified data sheet tolerance, the Zener voltage also varies with temperature and current. This voltage characteristic limits the accuracy to which a simple Zener-based regulator can function. As we continue, keep in mind the Zener's limitations and realize that, although it may not be well suited to directly regulating digital logic voltages, it can come in handy in less-restrictive power applications including battery charging, power supply clamping (e.g., preregulation), and coarse threshold comparison.

Figure 17.5 shows a Zener diode used in a shunt regulator circuit. Note that the cathode is at a higher voltage than the anode and that the Zener diode is identified with a Z-curve at the cathode. There are several common graphical representations for Zener diodes, but most involve some variation of a cathode Z-curve. This particular circuit uses the 5.1-V 1N4733A Zener diode with a 100-Ω

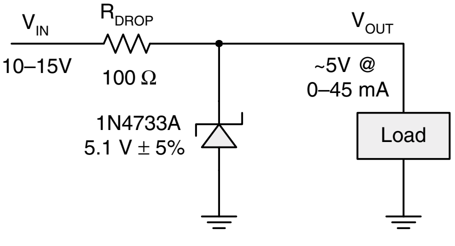

FIGURE 17.5 Zener diode shunt regulator.