PHYSICS APPLIED

LED

Another useful device is a **light-emitting diode** (LED), invented in the 1960s. When a *pn* junction is forward biased, a current begins to flow. Electrons cross from the *n* region into the *p* region and combine with holes, and a photon can be emitted with an energy approximately equal to the band gap, E_g (see Figs. 29–23c and 29–26). Often the energy, and hence the wavelength, is in the red region of the visible spectrum, producing the familiar LED displays on VCRs, CD players, car instrument panels, digital clocks, and so on. Infrared (i.e., nonvisible) LEDs are used in remote controls for TV, DVDs, and stereos. New types of LEDs emit other colors, and LED "bulbs" are beginning to replace other types of lighting in applications such as flashlights, traffic signals, car brake lights, and outdoor signs, billboards, and theater displays. LED bulbs, sometimes called **solid-state** lighting, are costly, but they offer advantages: they are long-lived, efficient, and rugged. LED traffic lights, for example, last 5 to 10 times longer than traditional incandescent bulbs, and use only 20% of the energy for the same light output. As car brake lights, they light up a fraction of a second sooner, allowing a driver an extra 5 or 6 meters (15–20 ft) more stopping distance at highway speeds.

Solar cells and photodiodes

Solar cells and **photodiodes** (Section 27–3) are *pn* junctions used in the reverse way. Photons are absorbed, creating electron–hole pairs if the photon energy is greater than the band gap energy, E_g. The created electrons and holes produce a current that, when connected to an external circuit, becomes a source of emf and power. *Particle detectors* (Section 30–13) operate similarly.

A diode is called a **nonlinear device** because the current is not proportional to the voltage. That is, a graph of current versus voltage (Fig. 29–28) is not a straight line, as it is for a resistor (which ideally *is* linear). Transistors are also *nonlinear* devices.

* 29–9 Transistors and Integrated Circuits

Transistors

A simple **junction transistor** consists of a crystal of one type of doped semiconductor sandwiched between two crystals of the opposite type. Both *npn* and *pnp* transistors are made, and they are shown schematically in Fig. 29–31a. The three semiconductors are given the names *collector, base,* and *emitter*. The symbols for *npn* and *pnp* transistors are shown in Fig. 29–31b. The arrow is always placed on the emitter and indicates the direction of (conventional) current flow in normal operation.

The operation of a transistor can be analyzed qualitatively—very briefly—as follows. Consider an *npn* transistor connected as shown in Fig. 29–32. A voltage $V_{\rm CE}$ is maintained between the collector and emitter by the battery $\mathscr{E}_{\rm C}$. The voltage applied to the base is called the *base bias voltage*, $V_{\rm BE}$. If $V_{\rm BE}$ is positive, conduction electrons in the emitter are attracted into the base. Since the base region is very thin (perhaps 1 μm), most of these electrons flow right across into the collector, which is maintained at a positive voltage. A large current, $I_{\rm C}$, flows between collector and emitter and a much smaller current, $I_{\rm B}$,

FIGURE 29–31 (a) Schematic diagram of *npn* and *pnp* transistors. (b) Symbols for *npn* and *pnp* transistors.

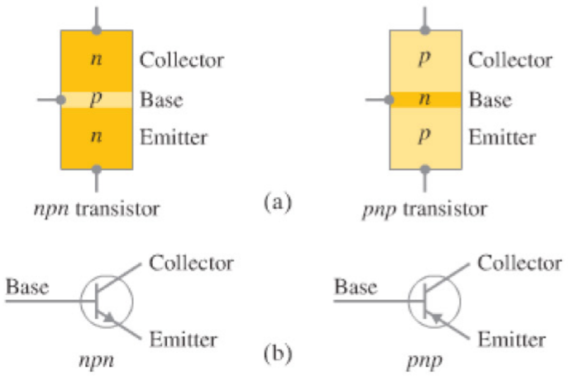

FIGURE 29–32 An *npn* transistor used as an amplifier.