GreenTech Application 1: *Solar Power*

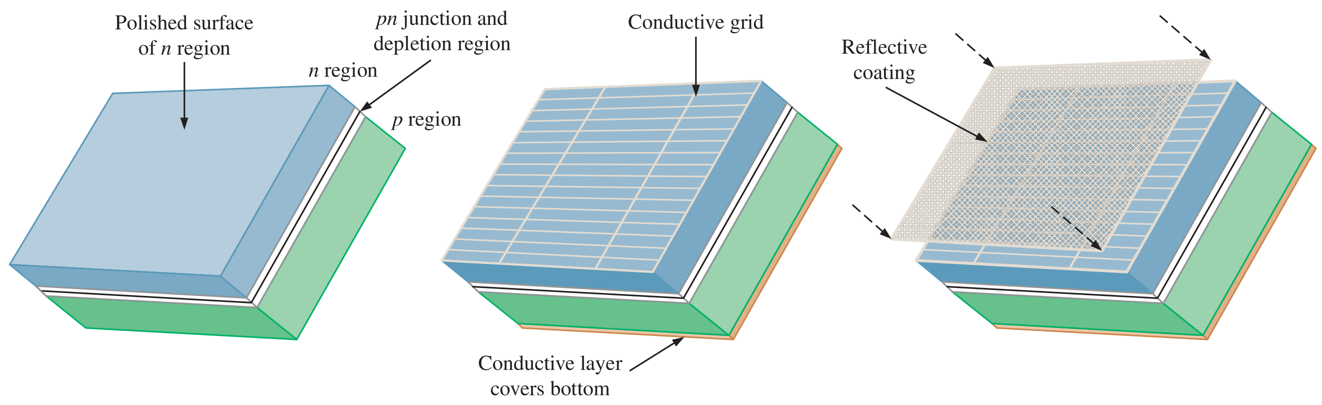
Photovoltaic (PV) Cell Structure and Operation

The key feature of a PV (solar) cell is the *pn* junction that was covered in Chapter 1. The **photovoltaic effect** is the basic physical process by which a solar cell converts sunlight into electricity. Sunlight contains photons or "packets" of energy sufficient to create electron-hole pairs in the *n* and *p* regions. Electrons accumulate in the *n*-region and holes accumulate in the *p* region, producing a potential difference (voltage) across the cell. When an external load is connected, the electrons flow through the semiconductor material and provide current to the external load.

The Solar Cell Structure Although there are other types of solar cells and continuing research promises new developments in the future, the crystalline silicon solar cell is by far the most widely used. A silicon solar cell consists of a thin layer or wafer of silicon that has been doped to create a *pn* junction. The depth and distribution of impurity atoms can be controlled very precisely during the doping process. The most commonly used process for creating a silicon ingot, from which a silicon wafer is cut, is called the *Czochralski method.* In this process, a seed crystal of silicon is dipped into melted polycrystalline silicon. As the seed crystal is withdrawn and rotated, a cylindrical ingot of silicon is formed.

Thin circular shaped-wafers are sliced from an ingot of ultra-pure silicon and then are polished and trimmed to an octagonal, hexagonal, or rectangular shape for maximum coverage when fitted into an array. The silicon wafer is doped so that the *n* region is much thinner than the *p* region to permit light penetration, as shown in Figure GA1–1(a).

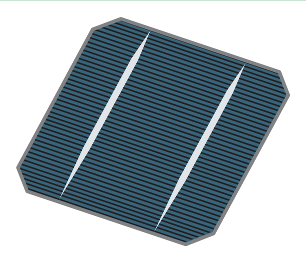
A grid-work of very thin conductive contact strips are deposited on top of the wafer by methods such as photoresist or silk-screen, as shown in part (b). The contact grid must maximize the surface area of the silicon wafer that be exposed to the sunlight in order to collect as much light energy as possible.



▲ **FIGURE GA1–1**

Basic construction of a PV solar cell.

The conductive grid across the top of the cell is necessary so that the electrons have a shorter distance to travel through the silicon when an external load is connected. The farther electrons travel through the silicon material, the greater the energy loss due to resistance. A solid contact covering all of the bottom of the wafer is then added, as indicated in the figure. Thickness of the solar cell compared to the surface area is greatly exaggerated for purposes of illustration.



▲ **FIGURE GA1–2**

A complete PV solar cell.

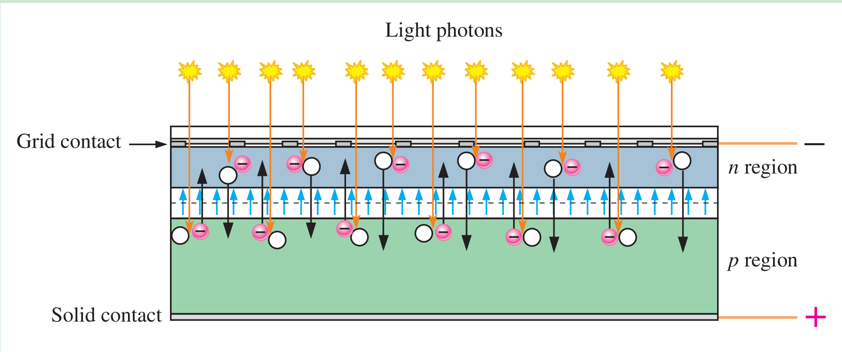
After the contacts are incorporated, an antireflective coating is placed on top the contact grid and *n* region, as shown in Figure GA1–1(c). This allows the solar cell to absorb as much of the sun's energy as possible by reducing the amount of light energy reflected away from the surface of the cell. Finally, a glass or transparent plastic layer is attached to the top of the cell with transparent adhesive to protect it from the weather. Figure GA1–2 shows a completed solar cell.

Operation of a Solar Cell As indicated before, sunlight is composed of photons, or "packets" of energy. The sun produces an astounding amount of energy. The small fraction of the sun's total energy that reaches the earth is enough to meet all of our power needs many times over. There is sufficient solar energy striking the earth each hour to meet worldwide demands for an entire year.

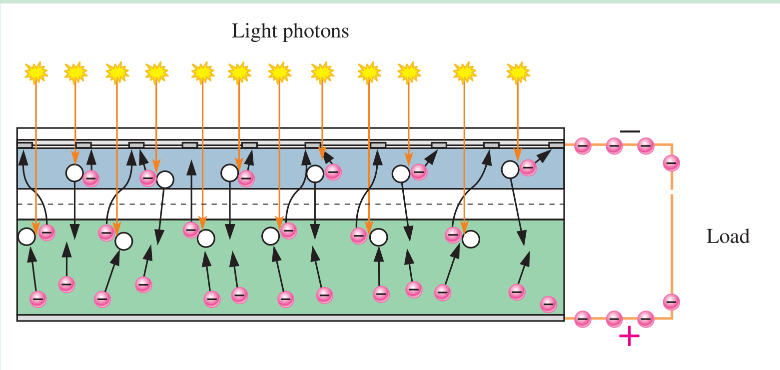
The *n*-type layer is very thin compared to the *p* region to allow light penetration into the *p* region. The thickness of the entire cell is actually about the thickness of an eggshell. When a photon penetrates either the *n* region or the *p*-type region and strikes a silicon atom near the *pn* junction with sufficient energy to knock an electron out of the valence band, the electron becomes a free electron and leaves a hole in the valence band, creating an *electron-hole pair.* The amount of energy required to free an electron from the valence band of a silicon atom is called the band-gap energy and is 1.12 eV (electron volts). In the *p* region, the free electron is swept across the depletion region by the electric field into the *n* region. In the *n* region, the hole is swept across the depletion region by the electric field into the *p* region. Electrons accumulate in the *n* region, creating a negative charge; and holes accumulate in the *p* region, creating a positive charge. A voltage is developed between the *n* region and *p* region contacts, as shown in Figure GA1–3.

▶ **FIGURE GA1–3**

Basic operation of a solar cell with incident sunlight.



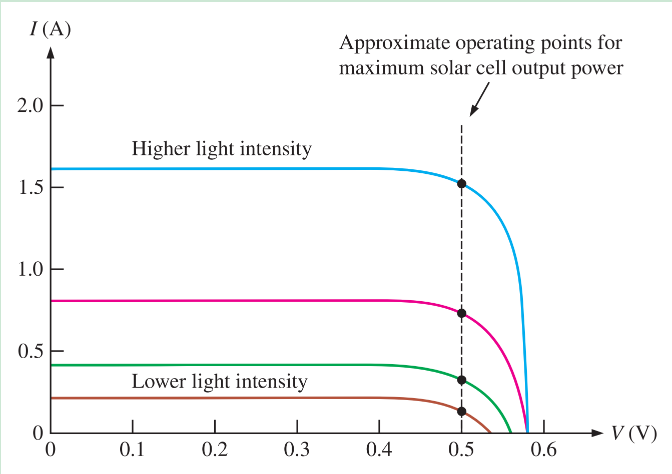
When a load is connected to a solar cell via the top and bottom contacts, the free electrons flow out of the *n* region to the grid contacts on the top surface, through the negative contact, through the load and back into the positive contact on the bottom surface, and into the *p* region where they can recombine with holes. The sunlight energy continues to create new electron-hole pairs and the process goes on, as illustrated in Figure GA1–4.



Solar Cell Characteristics

Solar cells are typically 100 cm^2 to 225 cm^2 in size. The usable voltage from silicon solar cells is approximately 0.5 V to 0.6 V. Terminal voltage is only slightly dependent on the intensity of light radiation, but the current increases with light intensity. For example, a 100 cm^2 silicon cell reaches a maximum current of approximately 2 A when radiated by 1000 W/m^2 of light.

Figure GA1–5 shows the *V-I* characteristic curves for a typical solar cell for various light intensities. Higher light intensity produces more current. The operating point for maximum power output for a given light intensity should be in the "knee" area of the curve, as indicated by the dashed line. The load on the solar cell controls this operating point ($R_L = V/I$).



◀ **FIGURE GA1–5**

V-I characteristic for a typical single solar cell from increasing light intensities.

In a solar power system, the cell is generally loaded by a charge controller or an inverter. A special method called *maximum power point tracking* will sense the operating point and adjust the load resistance to keep it in the knee region. For example, assume the solar cell is operating on the highest intensity curve (blue) shown in Figure GA1–5. For maximum power (dashed line), the voltage is 0.5 V and the current is 1.5 A. For this condition, the load is

$$R_L = \frac{V}{I} = \frac{0.5\text{ V}}{1.5\text{ A}} = 0.33\ \Omega$$

Now, if the light intensity falls to where the cell is operating on the red curve, the current is less and the load resistance will have to change to maintain maximum power output as follows:

$$R_L = \frac{V}{I} = \frac{0.5\text{ V}}{0.8\text{ A}} = 0.625\ \Omega$$

If the resistance did not change, the voltage output would drop to

$$V = IR = (0.8\text{ A})(0.33\text{ W}) = 0.264\text{ V}$$

resulting in less than maximum power output for the red curve. Of course, the power will still be less on the red curve than on the blue curve because the current is less.

The output voltage and current of a solar cell is also temperature dependent. Notice in Figure GA1–6 that for a constant light intensity the output voltage decreases as the temperature increases but the current is affected only by a small amount.