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Solar cell

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Content

A semiconductor electrical junction device which directly and efficiently absorbs the radiant energy of sunlight and converts it into electrical energy. Solar cells may be used individually as light detectors, for example in cameras, or connected in series and parallel to obtain the required values of current and voltage for electric power generation.

Most solar cells are made from single-crystal silicon and have been very expensive for generating electricity, but have found application in space satellites and remote areas where low-cost conventional power sources have been unavailable. Research has emphasized lowering solar cell cost by improving performance and by reducing materials and manufacturing costs. One approach is to use optical concentrators such as mirrors or Fresnel lenses to focus the sunlight onto smaller-area solar cells. Other approaches replace the high-cost single-crystal silicon with thin films of amorphous or polycrystalline silicon, gallium arsenide, cadmium sulfide, or other compounds.

Solar radiation

The intensity and quality of sunlight are dramatically different outside the Earth's atmosphere from that on the surface of the Earth. The number of photons at each energy is reduced upon entering the Earth's atmosphere due to reflection, to scattering, or to absorption by water vapor and other gases. Thus, while the solar energy at normal incidence outside the Earth's atmosphere is 1.36 kW/m^2 (the solar constant), on the surface of the Earth at noontime on a clear day the intensity is about 1 kW/m^2.

On clear days the direct radiation is about 10 times greater than the diffuse radiation, but on overcast days the sunshine is entirely diffuse. The mean annual solar energy falling on the Earth's surface varies greatly from one location to another. The sunniest regions of the globe receive about 2500 kWh/m^2 per year of total sunshine on a horizontal surface. The Earth receives about 10^{18} kWh of solar energy each year. The worldwide annual energy consumption is about 80×10^{12} kWh, so that from a purely technical viewpoint, the world energy consumption corresponds to the sunlight received on about 0.008% of the surface of the Earth. *See also:* **Solar radiation (/content/solar-radiation/633700)**

Principles of operation

The conversion of sunlight into electrical energy in a solar cell involves three major processes: absorption of the sunlight in the semiconductor material; generation and separation of free positive and negative charges to different regions of the solar cell, creating a voltage in the solar cell; and transfer of these separated charges through electrical terminals to the outside application in the form of electric current.

In the first step the absorption of sunlight by a solar cell depends on the intensity and quality of the sunlight, the amount of light reflected from the front surface of the solar cell, the semiconductor band-gap energy which is the minimum light (photon) energy the material absorbs, and the layer thickness. Some materials such as silicon require tens of micrometers' thickness to absorb most of the sunlight, while others such as gallium arsenide, cadmium telluride, and copper sulfide require only a few micrometers.

When light is absorbed in the semiconductor, a negatively charged electron and positively charged hole are created. The heart of the solar cell is the electrical junction which separates these electrons and holes from one another after they are created by the light. An electrical junction may be formed by the contact of: a metal to a semiconductor (this junction is called a Schottky barrier); a liquid to a semiconductor to form a photoelectrochemical cell; or two semiconductor regions (called a *pn* junction).

The fundamental principles of the electrical junction can be illustrated with the silicon *pn* junction. Pure silicon to which a trace amount of a fifth-column element such as phosphorus has been added is an *n*-type semiconductor, where electric current is carried by free electrons. Each phosphorus atom contributes one free electron, leaving behind the phosphorus atom bound to the crystal structure with a unit positive charge. Similarly, pure silicon to which a trace amount of a column-three element such as boron has been added is a *p*-type semiconductor, where the electric current is carried by free holes. Each boron atom contributes one hole, leaving behind the boron atom with a unit negative charge. The interface between the *p*- and *n*-type silicon is called the *pn* junction. The fixed charges at the interface due to the bound boron and phosphorus atoms create a permanent dipole charge layer with a high electric field. When photons of light energy from the Sun produce electron-hole pairs near the junction, the built-in electric field forces the holes to the *p* side and the electrons to the *n* side (**Fig. 1**). This displacement of free charges results in a voltage difference between the two regions of the crystal, the *p* region being plus and the *n* region minus. When a load is connected at the terminals, electron current flows in the direction of the arrow, and electrical power is available at the load. *See also:* **Photovoltaic cell (/content/photovoltaic-cell/512100)**; **Photovoltaic effect (/content/photovoltaic-effect/512110)**; **Semiconductor (/content/semiconductor/614010)**; **Semiconductor diode (/content/semiconductor-diode/614020)**

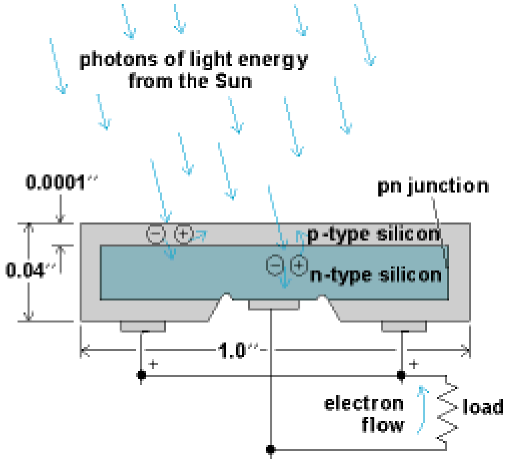

Fig. 1 Cross-sectional view of a silicon *pn* junction solar cell, illustrating the creation of electron pairs by photons of light energy from the Sun. 0.0001″ = 2.5 μm; 0.04″ = 1 mm; 1.0″ = 25 mm.

Characteristics

The short-circuit current of a typical silicon *pn*-junction solar cell is directly proportional to light intensity and amounts to 28 mA/cm^2 at full sunlight (1000 W/m^2). The open-circuit voltage rises sharply under weak light and saturates at about 0.6 V for radiation between 200 and 1000 W/m^2. The maximum power output from the solar cell irradiated by full sunlight is about 11 mW/cm^2 at an output voltage of 0.45 V.

Under these operating conditions the overall conversion efficiency from solar to electrical energy is 11%. The output power as well as the output current is of course proportional to the irradiated surface area, whereas the output voltage can be increased by connecting cells in series just as in an ordinary chemical storage battery. Experimental samples of silicon solar cells have been produced which operate at efficiencies up to 18%, but commercial cell efficiency is around 10–12% under normal operating conditions.

Using optical concentration to intensify the light incident on the solar cell, efficiencies above 20% have been achieved with silicon cells and above 25% with gallium arsenide cells. The concept of splitting the solar spectrum and illuminating two optimized solar cells of different band gaps has been used to achieve efficiencies above 28%, with expected efficiencies of 35%. Thin-film solar cells have achieved between 4 and 9% efficiency and are expected in low-cost arrays to be above 10%.

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Arrays

Individual silicon solar cells or photovoltaic cells are about 100 cm^2 (15.5 in.^{2}) of surface area in size. At a 15% conversion efficiency, such a cell can deliver about 1.4 W at 0.5 V when in full sunlight. To obtain higher power and higher voltage, a number of cells must be assembled in panels or arrays (**Fig. 2**). Modules are of two basic types: flat plates (crystalline silicon or thin film) and concentrators. Cells may be connected in series to multiply their output voltage and in parallel to multiply their output current. Cells operated in series must be closely matched in short-circuit current since the overall performance of a solar cell array is limited by the cells having the lowest current.

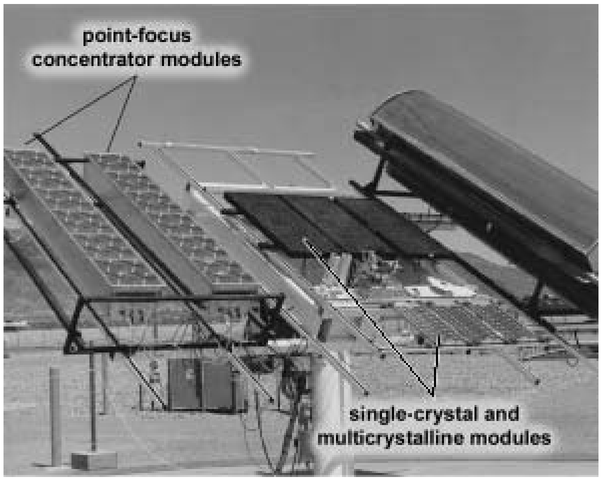

Fig. 2 Silicon solar cells assembled into modules and arrays to obtain higher voltage and current output. (*Sandia National Laboratories*)

Applications

Although the photovoltaic effect was discovered by A. C. Becquerel in 1839, practical solar cells made of silicon crystals were not developed until 1955. Beginning with *Vanguard 1*, launched in 1958, silicon solar cell arrays have become the almost exclusive power source for satellites. *See also:* **Space power systems (/content/space-power-systems/639200)**

Solar cell arrays have been used primarily to power small remote electrical loads that would otherwise be impractical or uneconomical to power by conventional means such as storage batteries or motor-generator sets. Solar cell arrays are sold worldwide to power such equipment as remote radio repeaters, navigational aids, consumer products, railroad signals, cathodic protection devices, and water pumps. Since most of the aforementioned uses require powering the load at times even when the Sun is not shining, electrical storage batteries are typically used in conjunction with solar cell arrays to provide reliable, continuous power availability.

Terrestrial uses take advantage of the ease of installation of photovoltaic arrays and the ease of adding or removing modules to meet changing electrical demands. These uses include agricultural, residential, commercial, and industrial applications (**Fig. 3**). When powering loads which require ac voltage, a static inverter is used to convert the dc voltage from the solar cell array into usable ac power. *See also:* **Solar energy (/content/solar-energy/633300)**

Fig. 3 A 2-MW photovoltaic array. (*Sacramento Municipal Utility District, California*)

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