

Photonics-Enabled Technologies

Photonics Principles in Photovoltaic Cell Technology



OP-TEC

Optics and Photonics Series

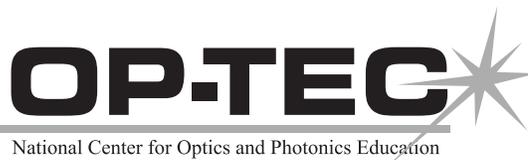
Photonics Principles in Photovoltaic Cell Technology

Photonics-Enabled Technologies

OPTICS AND PHOTONICS SERIES

**OP-TEC: The National Center of Optics
and Photonics Education**

An NSF ATE Project



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PREFACE

This module addresses the role of optics and lasers in the field of biomedicine. OP-TEC treats biomedicine as a *photonics-enabled* technology. The current OP-TEC series on photonics-enabled technologies comprises modules in the areas of manufacturing, biomedicine, forensic science and homeland security, optoelectronics, and environmental monitoring, as listed below. (This list will expand as the OP-TEC series grows. For the most up-to-date list of OP-TEC modules, visit <http://www.op-tec.org>.)

Manufacturing

Laser Welding and Surface Treatment

Laser Material Removal: Drilling, Cutting, and Marking

Lasers in Testing and Measurement: Alignment Profiling and Position Sensing

Lasers in Testing and Measurement: Interferometric Methods and Nondestructive Testing

Environmental Monitoring

Basics of Spectroscopy

Spectroscopy and Remote Sensing

Spectroscopy and Pollution Monitoring

Biomedicine

Lasers in Medicine and Surgery

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Diagnostic Applications of Lasers

Forensic Science and Homeland Security

Lasers in Forensic Science and Homeland Security

Infrared Systems for Homeland Security

Imaging System Performance for Homeland Security Applications

Optoelectronics

Photonics in Nanotechnology

Other

Photonics Principles in Photovoltaic Cell Technology

The modules pertaining to each technology can be used collectively as a unit or separately as stand-alone items, as long as prerequisites have been met.

For students who may need assistance with or review of relevant mathematics concepts, a review and study guide entitled *Mathematics for Photonics Education* (available from CORD) is highly recommended.

The original manuscript of this module was prepared by Alfred Ducharme and edited by John Souders (CORD) and Larry DeShazer. Formatting and artwork were provided by Mark Whitney and Kathy Kral (CORD).

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INTRODUCTION

The dependence on foreign sources of energy such as petroleum has led to the emergence of alternative energy technologies. Currently, the most reliable and unlimited alternative energy source is solar power. In fact heat and light from the sun represent the source of nearly all of the renewable energy on Earth. Energy produced from the flow of wind and water is also the result of the sun's power absorbed by our planet. The current global power consumption is approximately 20 tera-watts (20×10^{12} watts) while the sun provides nearly 90,000 tera-watts. This means that if solar conversion technologies were utilized on a large scale, only one tenth of one percent conversion efficiency would be required to meet current demands.

Solar energy can be converted to heat or directly to electricity. A solar-heated pool is an example of a solar-to-heat application. Black panels are placed on the roof and water from a pool is pumped through a loop of narrow tubes embedded in each panel. The black material absorbs the sun's energy that in turn heats the water. This is the most basic application of solar energy conversion. The conversion of solar energy directly to electricity is achieved using photovoltaic cells. These cells are made from thin sheets of silicon, the standard material used in integrated circuits. Incident light produces a voltage similar to a battery. When the cell is attached to a load, the current generated can power electrical circuits.

The conversion of solar energy to electricity using photovoltaic cells, called simply solar cells, will be the focus of this module. We will begin with the fundamental characteristics of photovoltaic cell technology and how it produces electricity. In the next sections, the manufacturing of photovoltaic cells and assembly into panels will be explained. Finally, how photovoltaic cells are employed to solve a variety of energy problems will be presented.

PREREQUISITES

The student should be familiar with the following before attempting to complete this module.

1. High school mathematics through intermediate algebra
2. CORD's Optics and Photonics Series Course 1, *Fundamentals of Light and Lasers*
3. CORD's Optics and Photonics Series Course 2, *Elements of Photonics*

OBJECTIVES

Upon completion of this module, you should be able to do the following:

- Describe how solar energy is converted to electricity.
- Explain the process of manufacturing photovoltaic cells and panels.
- Understand the various circuit connections that can be used with solar panels.
- Explain how solar energy is concentrated to achieve higher conversion efficiencies.
- Describe storage techniques for collecting solar-generated electricity.
- Know how to test the performance of solar cells.
- Understand several different applications of solar cells.
- Explain future applications of photovoltaic technology.

SCENARIO

Harold Jones has been assigned to a program whose objective is to develop an independently powered electronic imaging system for use in the field. No power generation will be available for the operation of this system. Harold must devise a means of powering the system for long periods of time without having to manually replace batteries. Harold has decided to utilize lead-acid batteries. According to his calculations, the system will operate for two days of continuous operation using the battery power unit. To power the system indefinitely, Harold will utilize a solar cell to replenish the battery during daylight hours. He must now design and test a solar cell system to recharge the battery supply.

BASIC CONCEPTS

Introduction to Solar Cells

What is a solar cell?

To begin our exploration of photovoltaic technology, it is first important to understand the terminology that will be utilized throughout this module. *Photovoltaic* is a term used to describe a semiconductor device made from silicon that converts light to electricity. A photovoltaic cell is a packaged device that utilizes the photovoltaic phenomenon. When photovoltaic cells are linked together into a circuit they are called a *photovoltaic module* or simply a *solar cell*. A collection of modules is referred to as a *panel* or *array* (Figure 1).

A photovoltaic cell consists of a several thin and very fragile layers of silicon. These layers appear metallic blue in color and are covered with thin silver lines. To keep the brittle silicon from breaking, it is adhered to a metal plate thick enough to add rigidity but not too thick as to

make the cell heavy. A single cell only covers a small area and doesn't generate enough electricity by itself to produce a useful amount of power. To increase area and power, cells are electrically connected to form a module or solar panel. The top silicon face of the panel requires isolation from damage and is usually covered by a resin or glass covering. Additional framing surrounding the panel enables it to be mounted and used in various applications.

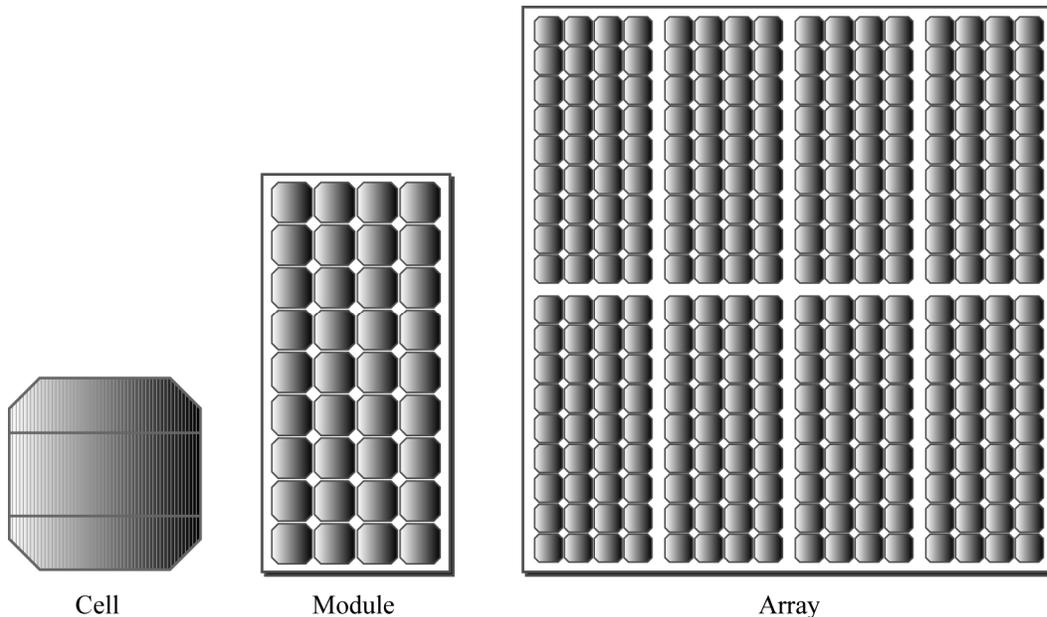


Figure 1 Photovoltaic cell, module, and array (or panel)

The performance of a solar panel is limited by two parameters: area and efficiency. The area of the panel determines how much solar energy it can collect. A large panel can collect more solar energy than a small panel simply because the area is larger. Efficiency is the ability of the solar panel to convert light to electricity. The efficiency depends on the quality of the manufacturing process, the purity of the materials, and the technology utilized. Different manufacturers use slightly different mixtures and construction techniques that can yield various efficiencies. The race for the optimal photovoltaic technology is ongoing with the goal being inexpensive and efficient solar panels.

How a photovoltaic cell operates

Atoms represent the basic building block of all materials and gases. At the center of the atom is the dense nucleus containing positively charged protons and neutral neutrons. Surrounding the nucleus is an electron cloud where individual electrons orbit the nucleus at well defined radii or shells. Depending on the element, there are a specific number of protons and an equal number of electrons. All known elements are cataloged in the Periodic Table, in which the number of protons in each element is the *atomic number* for that element.

A complete explanation of atomic theory is beyond the scope of this module. In simplified terms, as the complexity of an atom increases towards higher atomic numbers so does the number of electrons orbiting the nucleus. Electrons orbit the nucleus like planets orbit the sun. The force that binds an electron to its nucleus is not gravitational (like the force that keeps the planets orbiting the sun) but electrostatic. This electrostatic force arises from the attraction of the opposite charges on a

proton and electron. Quantum theory defines discrete electron orbit distances or shells. In addition, it limits the number of electrons that can exist in a single shell. The shells with the greatest radii are called the *outer shells*. The electrons in the outer shells of an atom also have the weakest electrostatic attraction to the nucleus since they are farthest from their proton counterparts.

The element silicon (atomic number 14) has a total of 14 electrons orbiting the nucleus. Quantum theory allows 2 electrons in the first shell, 8 electrons in the second shell, 18 electrons in the third shell, and so on. The general formula is $2n^2$ where n is the n th shell. Therefore, silicon has 2 electrons in the first shell, 8 electrons in the second shell, and the remaining 4 electrons in the third or outer shell. These 4 electrons are vital to our understanding of how photovoltaic cells operate. These electrons, called *valence electrons*, form bonds between atoms. This type of bonding, called *covalent bonding*, occurs when pairs of electrons are shared between two atoms. Since silicon has 4 valence electrons, it can bond to 4 other silicon atoms. Through this sharing, silicon atoms create a condition in their third electron shell where all subshells are filled. This allows silicon atoms to form complex crystalline structures.

Pure silicon, also referred to as *single crystal silicon*, would not facilitate the conversion of light to electricity. Electric current is the flow of electrons through a material. This requires extra electrons that pure silicon does not provide, since pure silicon in crystalline form uses all of the valence electrons to form the crystal structure or lattice. Consequently, pure silicon has to be modified with impurities in a process called *doping*. This process adds electrons to the material and can add sites within the material that attract electrons. These sites are called *holes*.

Atoms of phosphorus can be added to pure silicon to produce additional electrons. The theory is that a phosphorus atom has 5 valence electrons in its outer shell. When the phosphorus is assembled into the silicon crystal lattice, 4 of these valence electrons form covalent bonds with adjacent silicon atoms. This leaves one electron that is free to leave the structure. This forms a new type of material called a *semiconductor*, meaning that it is both an insulator and a conductor. Electrons not needed for bonding are free to travel to other atoms. Specifically, because the addition of phosphorus atoms provides additional electrons that are negatively charged, we call this an n-type semiconductor (where “n” indicates an average negative charge).

In the same manner, we can produce a p type semiconductor (where “p” indicates an average positive charge). This semiconductor provides the holes for our photovoltaic cell. For this material, boron atoms are added to pure silicon. Boron has 3 valence electrons. When incorporated into the silicon lattice structure, it results in a missing covalent bond that we call a hole. These holes are free to move throughout the lattice. This movement is equivalent to a flow of positive charge.

A photovoltaic cell is formed when a layer of n-type semiconductor is placed on a layer of p-type semiconductor. See Figure 2. When this occurs electrons in the n-type material diffuse into the p-type material and the holes in the p-type material diffuse into the n-type material. This creates a layer

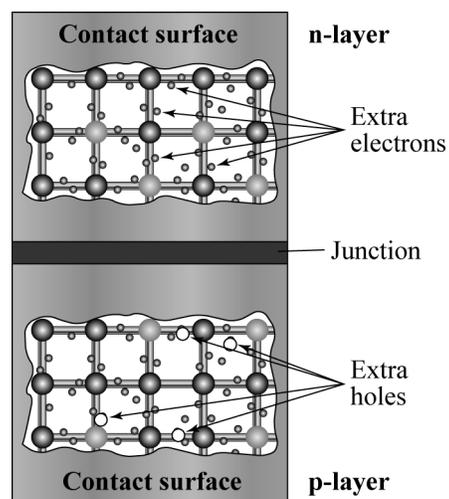


Figure 2 Illustration of p-n junction and n- and p-layers in a photovoltaic cell

of positive charges and negative charges at the surface of these materials which is illustrated in Figure 3 as “plus” and “minus” signs. Additionally a region develops between these two surfaces called a junction. The diffused charges on the surfaces of the n and p-type materials generate an electric field across the junction which eventually stops the diffusion process. Given this configuration of the photovoltaic cell, an external energy must be introduced to generate an electrical current and this is where light plays a role.

Light is made up of tiny bundles of energy with no mass called photons. The amount of energy in a single photon is determined from its wavelength or color. This is expressed mathematically as,

$$E = \frac{hc}{\lambda} \quad (1)$$

where h is Planck’s constant (6.626×10^{-34} joules·seconds), c is the speed of light (3.0×10^8 meters/second), and λ is the wavelength of the light in meters. Joules is the standard unit of energy used by the International System of Units (abbreviated SI).

Example 1: Calculating the energy in photons

Given: The wavelength of light 1×10^{-6} meters.

Find: Find the energy in 10 billion photons in joules.

Solution

Using $E = \frac{hc}{\lambda}$, calculate the energy of a single photon.

$$E = \frac{hc}{\lambda} = \frac{(6.626 \times 10^{-34} \text{ J} \cdot \text{s})(3.0 \times 10^8 \frac{\text{m}}{\text{s}})}{1 \times 10^{-6} \text{ meters}}$$

$$E = 1.99 \times 10^{-19} \text{ J}$$

$$E = (1.99 \times 10^{-19} \text{ J})(10 \times 10^9) = 1.99 \times 10^{-9} \text{ J}$$

When photons of sufficient energy interact with atoms in the photovoltaic cell, electrons in these atoms can move from the valence band to the conduction band. This generates mobile electron-hole pairs. Typically these pairs will recombine. However, if they are in or near the photovoltaic cell junction, they come under the influence of the electric field with holes (represented by circled “plus” signs in Figure 3) being swept into the p-type material and electrons (represented by circled “minus” signs in Figure 3) into to n-type material. This influence is shown in Figure 3 and is called the *photovoltaic effect*. The separation of these photon induced charges creates a voltage difference between the p and n regions. When a load is connected between them, an electrical current results which supplies power to the circuit.

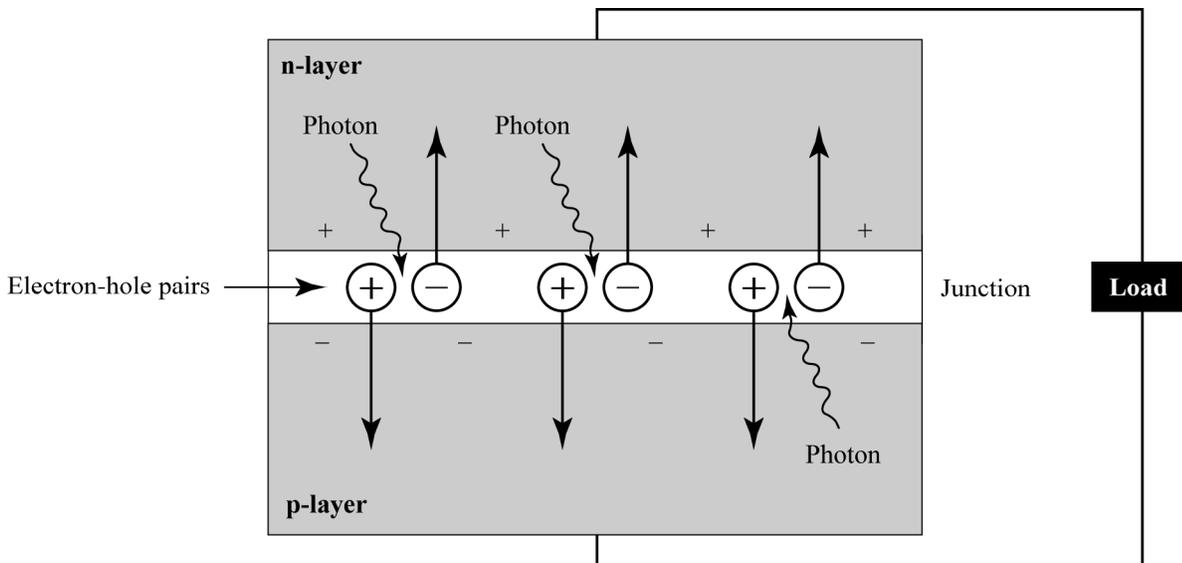


Figure 3 Photon absorption in photovoltaic cell

We said the photons must have sufficient energy to cause the photovoltaic effect. What is this energy? The difference between the valence and conduction bands is called the *band-gap energy*. Photons must have enough energy to raise an electron from the valence to the conduction band. The band-gap energy defines the operational wavelength range of the photovoltaic cell. Observing Equation 1, the wavelength parameter is in the denominator. Therefore, shorter wavelengths, blue photons, have more energy than longer wavelength, red photons. The band-gap energy limits the operation of the photovoltaic cell to photons with wavelengths shorter than the cut-off wavelength. Lower band-gap energy photovoltaic cells can utilize more of the light provided by the sun.

Sunlight

The sun is described in physics and optics as a *blackbody radiator*. This topic was covered in Course 1, *Fundamentals of Light and Lasers*, but a brief review is included here. An *emission spectrum* is a measure of the amount of light power over a range of wavelengths. All light sources have an associated emission spectrum. For example, a monochromatic (single color or wavelength) laser has an emission spectrum that is very narrow and, when plotted over a range of wavelengths, would appear as a single lone spike at the laser wavelength. Other sources typically have much wider emission spectra.

A blackbody is an ideal object that absorbs all electromagnetic radiation that interacts with its surface. This means that none of the radiation is reflected or transmitted—a theoretical possibility that can only be approximated in nature. This makes blackbodies excellent sources of thermal radiation since the emitted spectra are directly proportional to their temperatures. The higher the temperature the greater the amount of radiation emitted. Blackbodies emit radiation in a smooth continuous spectrum that includes visible and infrared light.

To understand how heated objects above 700 K appear to our eyes, consider a piece of steel heated in a fire or forge. As the heating process begins, soot forms on the steel and no light is seen to be emitted. The longer the steel is in the fire the higher its average temperature becomes. At first the steel glows with a dull deep red color that changes to red and then to orange. Finally,

the steel begins to glow white or what we call *white-hot*. The progression of color is consistent with the behavior of heated bodies that emit closer to the center of the visible spectrum as the temperature is increased.

Mathematically, the spectrum of blackbody radiation can be calculated using Planck's law of blackbody radiation as

$$M_{\lambda}(\lambda, T) = \frac{2\pi hc^2}{\lambda^5 [e^{hc/\lambda kT} - 1]} \left[\frac{\text{W}}{\text{cm}^2 \mu\text{m}} \right] \quad (2)$$

The constants used in this equation are:

Spectral exitance $\equiv M_{\lambda}(\lambda, T)$

Planck's constant $\equiv h = 6.6 \times 10^{-34} \text{ J} \cdot \text{s}$

Boltzmann's constant $\equiv k = 1.38 \times 10^{-23} \text{ J/K}$

Speed of light $\equiv c = 3 \times 10^8 \text{ m/s}$

This equation is used to determine the spectral output, also called *exitance*, for a given body heated to a temperature, T , in Kelvin. If a wavelength, λ , is specified, the exitance at that wavelength is determined. A plot for a family of blackbodies is given in Figure 4.

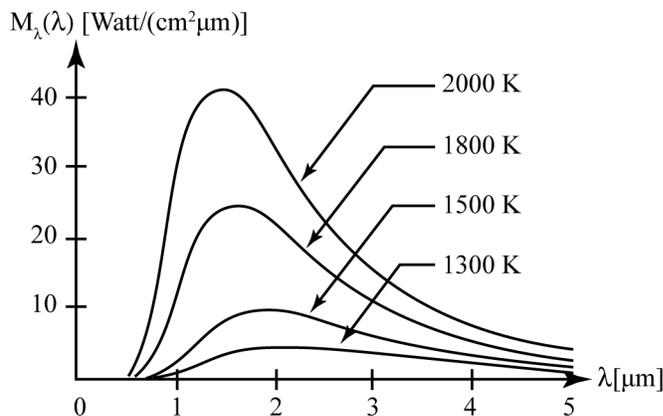


Figure 4 Plots of spectral exitance for blackbodies at 1300 K, 1500 K, 1800 K, and 2000 K

The sun is a blackbody radiator with an equivalent temperature of approximately 5900 K. Before the sun's radiation enters Earth's atmosphere (extraterrestrial), its emission spectrum is equivalent to a blackbody spectrum that can be calculated theoretically. As the light from the sun passes through the atmosphere it interacts with molecules such as water, carbon dioxide, and ozone. These molecules absorb wavelengths that excite them and reduce the resulting power incident on Earth's surface. The once continuous emission spectrum is changed to one with jagged features (Figure 5).

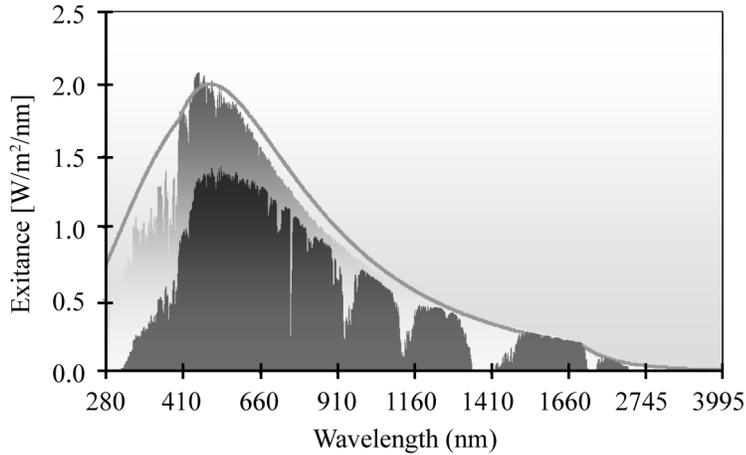


Figure 5 Comparison of 5900 K blackbody (grey line), extraterrestrial solar spectrum (light gray) and solar spectrum at Earth's surface (dark gray)

Responsivity

Photovoltaic cells convert photon energy to electrical power. As we have learned, the energy of a single photon is related to its wavelength using Equation 1. Additionally, a specific amount of energy is required to move electrons into the conduction band and produce a current. This band-gap energy is governed by the type of material used to fabricate the photovoltaic cell. In most cases the material is silicon doped with phosphor and boron atoms. The band-gap energy of silicon in electron volts is 1.12 eV. The cut-off wavelength, the longest wavelength that can create a current, can be found using the equation below. Starting from Equation 1, we can simplify the expression in terms of microns and electron volts.

$$E_{\text{gap}} [\text{eV}] = \frac{hc}{\lambda_{\text{cut-off}}} = \frac{6.6 \times 10^{-34} \text{ J}\cdot\text{s} \times 3 \times 10^8 \frac{\text{m}}{\text{s}}}{\lambda_{\text{cut-off}} [\mu\text{m}] \times 10^{-6} \frac{\text{m}}{\mu\text{m}}} \times \frac{1 \text{ eV}}{1.6 \times 10^{-19} \text{ J}}$$

$$E_{\text{gap}} [\text{eV}] = \frac{1.24}{\lambda_{\text{cut-off}} [\mu\text{m}]} \quad (3)$$

$$\lambda_{\text{cut-off}} [\mu\text{m}] = \frac{1.24}{E_{\text{gap}} [\text{eV}]}$$

For silicon with a band-gap energy of 1.12 eV, using Equation 3, the cut-off wavelength is 1.107 μm or 1107 nm.

The effect of photon wavelength to move electrons to the conduction band is described in Figure 6.

Photons with wavelengths shorter than the cut-off wavelength have more than enough energy to move electrons into the conduction band and generate a current. Consequently, photons with wavelengths longer than the cut-off wavelength cannot move electrons to the conduction band. When that happens, no current is generated.

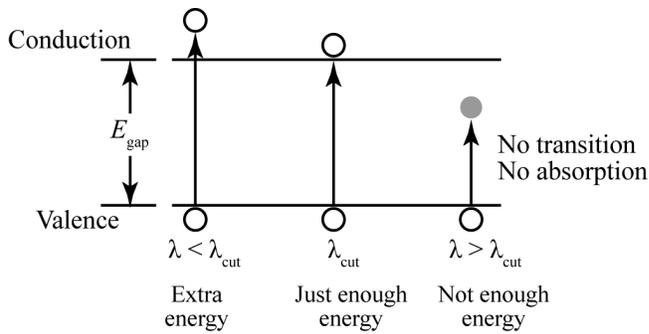


Figure 6 Conversion of photon energy to generation of free electrons in the conduction band of a semiconductor

The relationship between incident photons and current production is called *responsivity*. An example responsivity plot as a function of wavelength for a silicon p-n junction device is shown in Figure 7.

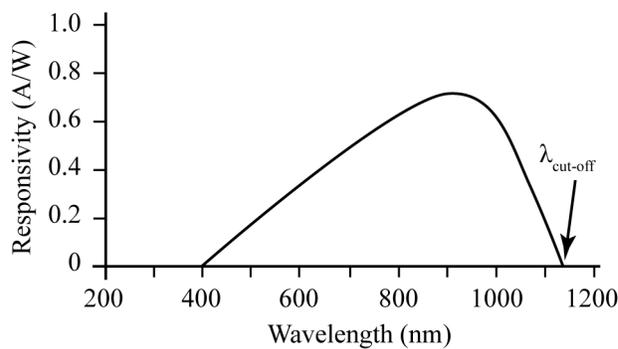


Figure 7 Responsivity as a function of wavelength for a silicon photodiode

The responsivity function describes the range of wavelengths that can be used to produce a current in a photovoltaic cell. The vertical axis gives the ratio of the amount of current produced (in amperes) for a given amount of optical power (in watts) incident on the photovoltaic cell.

The comparison between silicon responsivity and the spectrum of the solar spectrum on Earth shows that only a portion of the sun's energy is converted to current by a photovoltaic cell (Figure 8). The absorbed energy by the photovoltaic cell represents approximately 60% of the solar spectrum. This percentage is a good rule-of-thumb when trying to determine how much energy is collected by a photovoltaic cell.

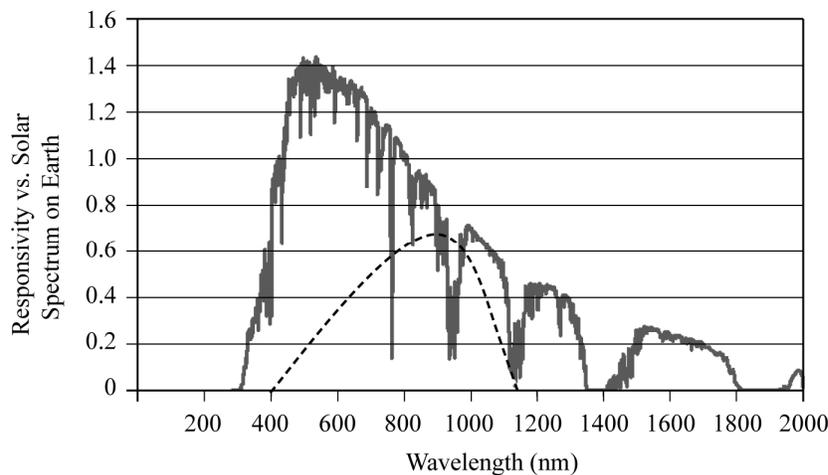


Figure 8 Comparison of silicon responsivity (dashed line) and solar spectrum on the surface of the Earth

Solar constant

The *solar constant* is the amount of solar radiation per unit area at the outer surface of Earth's atmosphere (extraterrestrial). This value fluctuates during the year (depending on the season) by about 7%. The average solar constant is 1,366 watts per square meter. In addition, the solar constant fluctuates over time by what are called *Milankovitch cycles*. Earth has been in a cooling cycle for some 6,000 years, which is expected to continue for the next 23,000 years. Therefore, the average solar constant is slowly being reduced in value due to the Milankovitch cycles.

Manufacturing Photovoltaic Cells

The primary objective of all manufacturing processes is to minimize cost while maximizing performance. Photovoltaic manufacturing techniques have progressed rapidly in the last few decades and new processes are emerging every year. In this section the most common and current techniques for producing photovoltaic cells will be discussed. The differences between these techniques lie primarily in the way the base material, silicon, is formed in flat cells. The explanation will begin with the production of the raw silicon material and then to how it is used in cells.

Silicon production

Silicon is essentially made from sand. It is one of the most common and easily obtainable raw materials used in the manufacturing of semiconductor devices. The process starts by obtaining pure sand in its white *quartz state* (i.e., containing no impurities or other elements). This pure silicon dioxide, SiO_2 , which is also called *silica* or *silox*, is reduced to molten silicon in an arc furnace where it is heated to 1650 °C (degrees Celsius). The carbon from the arc reacts with the silicon dioxide to produce carbon dioxide, CO_2 , and silicon in molten form. This process yields metallurgical-grade silicon that is useful for many applications but not pure enough for semiconductor manufacturing.

The silicon is further refined by generating a single crystal of ultra-pure silicon. This is accomplished using a method known as the *Czochralski process*. This process starts by introducing previously refined pure single crystal silicon to the molten silicon. This so called *seed* crystal resides at the end of a drawing rod. The tip of the rod containing the seed is dipped into the molten silicon and then drawn out over a long period of time. Silicon in the crucible is added to the crystal, forming a long rod or *boule* of pure single crystal silicon. Boules of single crystal silicon are typically several inches in diameter (6–10 inches) and many feet long.

The resulting silicon boule is then sliced into wafers approximately 0.012 inch thick with a diameter equal to the size of the boule. A single boule can produce thousands of wafers. In most cases, both sides of the wafer are polished with one side being highly polished. These wafers are used in the production of many types of silicon-based integrated circuits as well as photovoltaic cells.

Fabricating the junction

When silicon is refined for photovoltaic cells, boron is introduced during the molten phase of production. This generates the p-type semiconductor—half of the p-n junction needed for the photovoltaic cell. Once the wafer is produced the back is protected and the entire wafer is heated in a diffusion furnace. During the heating, phosphor is introduced into the furnace. Some of the phosphor atoms diffuse themselves into the top of the wafer, forming the n-type semiconductor—the other half of the p-n junction.

Creating contacts

The wafers now have the needed p-n junction. To complete the cell, the front and back of the junction are furnished with contacts. These contacts, called *ohmic contacts*, must have extremely low resistance to achieve high efficiency. They must also be durable since the cell will need to be soldered to other cells. The back contact can be a single metal layer since light does not need to pass through it. Optically this metal backing can also increase efficiency by reflecting light back into the p-n junction. A metal substrate is often used to add rigidity and durability to the delicate silicon wafer. The top contacts should be thin but still cover a large area to improve efficiency by reducing resistance. These contacts, called *finger contacts* (Figure 9), must be thin to maximize light transmittance. A typical manufacturing process uses palladium-silver etching. In this process the metals are evaporated in a vacuum chamber. The metal forms in openings in a mask placed on top of the photovoltaic cell. A thicker metal layer is then electroplated on top of the delicate finger contacts. The resulting photovoltaic cell is now ready for assembly into a module containing many individual cells.

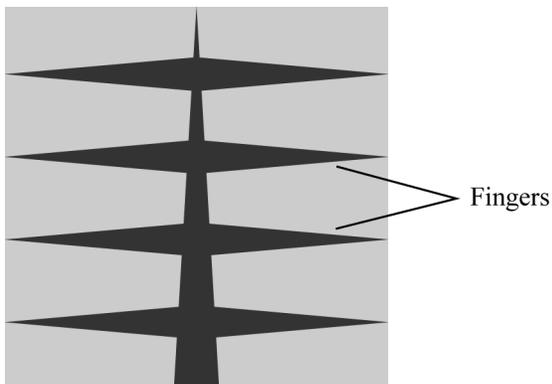


Figure 9 *A single photovoltaic cell with finger contacts*

Other manufacturing techniques

The previously described photovoltaic cell manufacturing technique is the oldest and most common method used. This is also the most expensive technique primarily because of the cost of the single-crystal-growth Czochralski process. This section would not be complete without mentioning newer processes.

The first is solar-grade silicon produced in a similar method as single crystal silicon. The difference is that solar-grade silicon still contains some of the impurities found in metallurgical-

grade silicon. However, the impurities are engineered to have less effect on photovoltaic applications. The promise of this less pure silicon is that it lowers cost without reducing the overall efficiency of the photovoltaic effect.

Some researchers believe that a single silicon crystal is not needed for photovoltaic cells. The proposed technique is to use a material with many individual crystals in a material called *polycrystalline silicon*. The accepted theory suggests that the electrical boundary between crystals would limit the efficiency of power conversion. Recent advances suggest that proper engineering can overcome this problem. If efficiencies of photovoltaic cells made from polycrystalline silicon can be increased, this advance could yield low-cost modules.

An amorphous silicon material lacks a crystalline structure. An example would be glass used for windows and other optics. Amorphous semiconductors can be manufactured using less complex and expensive sputtering techniques. This technique was used to produce photovoltaic cells for calculators and watches in the 1980s. These cells were inexpensive but did not yield high power-conversion efficiencies. Several companies are working to produce higher-efficiency amorphous silicon photovoltaic cells.

Photovoltaic Modules

The photovoltaic cells by themselves can only produce minute quantities of power. A typical cell will only produce a voltage in bright sunlight of tenths of a volt. Assembly into electrically connected modules is required to increase the amount of useful power generated.

Series and parallel connections

A solar cell, when illuminated, behaves like a battery producing a potential difference or voltage across its leads. Series connections increase the overall voltage difference while the current produced remains the same. Conversely, parallel connections increase the overall current achievable while the voltage remains the same. Therefore, cells are connected in series to obtain the desired voltage. These strings are then connected in parallel to increase the maximum current output. A module is a wired configuration of cells that reaches a design power goal. The power capability of combinations of photovoltaic cells is calculated by multiplying the maximum current by the maximum voltage.

Several techniques are used to make the wire connections between cells. One of the older techniques is to use nickel-top finger contacts that are tinned using traditional wave-soldering machines (Figure 10). More reliable connections, used in applications such as satellites, use soldered silver-palladium fingers. Most large-volume module production today utilizes silk-screening techniques. Final connections are then achieved using spot-welding.

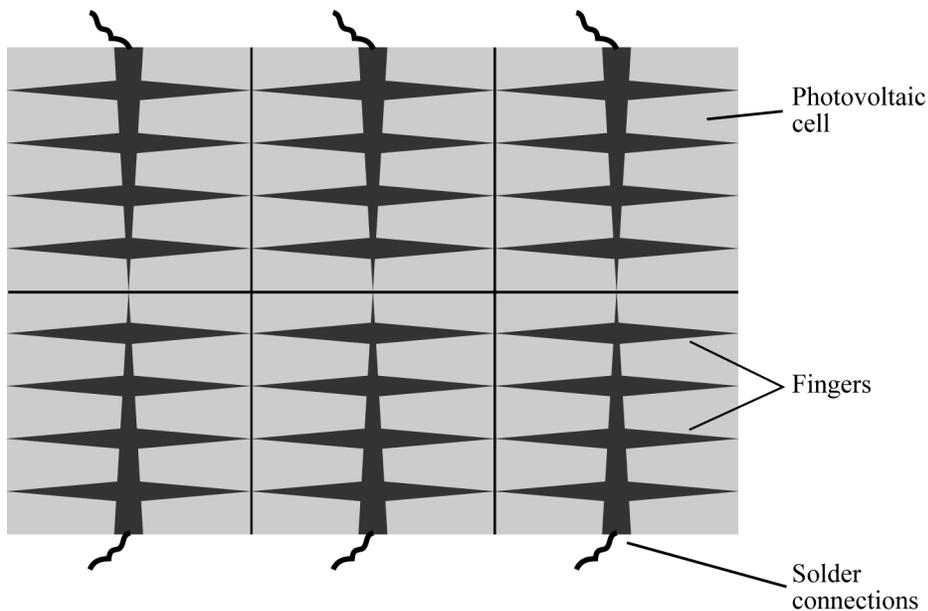


Figure 10 Typical finger contact arrangement used on photovoltaic cell

Sealing modules

The solder connections, finger contacts, and the silicon are fragile and must be protected from environmental conditions. Glass cover plates are often used because they are optically transparent and do not degrade over time (Figure 11). However, glass makes the module heavy and very rigid. Coating techniques are often used to produce lighter modules. Standard coatings are ethylene vinyl acetate and polycarbonate plastics. While these have their own trade-offs, overall they are less expensive than glass and are flexible. However, these coatings degrade over time, primarily, due to ultraviolet light that reduces transparency.

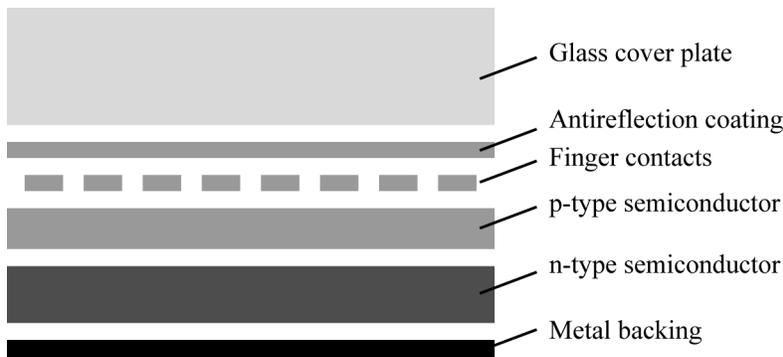


Figure 11 Overall construction of photovoltaic module

Antireflection coatings

Silicon has a high index of refraction between 3.5 and 5.5 over the wavelength range from 400 nm to 1100 nm. Since the light incident on a photovoltaic cell is near-normal incidence, the Fresnel equation can be used to calculate the amount of reflected light from a photovoltaic:

$$R = \left(\frac{n_1 - n_2}{n_1 + n_2} \right)^2 \quad (4)$$

where n_1 is the index of medium above the photovoltaic (air) and n_2 is the index of silicon. At the peak responsivity of a photovoltaic, 950 nm (see Figure 6), the index is 3.6. Using Equation 4, the reflected light percentage is 32%. Therefore, approximately 1/3 of the light incident on the photovoltaic module and individual cells is lost due to reflection.

A special photonic coating can be used to reduce the amount of reflected light. This coating is called an *antireflection coating* (or simply *AR coating*). A typical coating is applied in a vacuum evaporation technique forming a layer only one-fourth the wavelength of visible light. The one-fourth-wavelength thickness is crucial to the operation of the coating. The incident light first reflects from the top surface of the antireflection coating. Most of the incident light travels into the coating until it encounters the photovoltaic cell. At this boundary a secondary reflection occurs. The path length of the light traveling from the top surface of the coating to the photovoltaic surface and back is equivalent to half the wavelength of the incident light. You will recall that in Course 1, *Fundamentals of Light and Lasers*, when two waves are out of phase by half a wavelength (180 degrees), destructive interference takes place. Since the reflected light rays are canceled by interference, the total light lost to reflection is reduced.

In Figure 12, the incident ray is drawn such that it is not normal to the front surface of the AR coating. This allows all reflected rays to be illustrated. Light incident on a photovoltaic cell is nearly normal to this surface, and the rays represented by Reflection 1 and Reflection 2 are 180 degrees out of phase. Thus, the reflected light is reduced and the transmitted light is increased. This is the operating principle of the antireflection coatings used on photovoltaic cells and other optical devices.

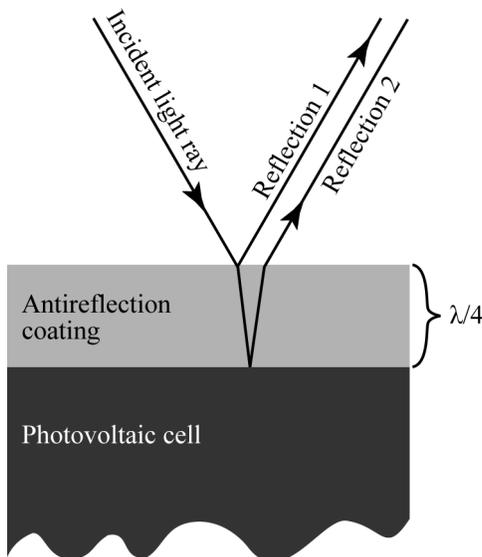


Figure 12 Diagram showing operation of antireflection coating

Materials used for AR coatings are silicon monoxide and titanium dioxide, both of which adhere well to silicon. These coatings reduce the light lost from reflection by an order of magnitude to around 3%. This significantly improves the performance of the photovoltaic cell and module.

Energy conversion efficiency

Photovoltaic cells are not able to convert every incoming photon to useful electrical power. Impurities in the materials, impedances of contacts, and reflection all limit the ability of the photovoltaic cell to do its job perfectly. This performance, called *energy conversion efficiency*, indicates just how well the photovoltaic cell is able to convert incoming light to current.

Typical photovoltaic cells have energy conversion efficiencies around 15%. This means that 15% of the incident optical power is converted to electricity. Recent advances in photovoltaic technologies have produced efficiencies as high as 40%. Every commercially available photovoltaic module will have an associated energy conversion efficiency; that information should be provided with the module by the manufacturer.

Improving the efficiency of photovoltaics is one of the most important criteria for making solar an alternative energy source. Cost is another very important criterion. Current research is focused on improving efficiency while reducing cost.

Solar Collection

The quantity called the *solar constant* discussed previously indicates that approximately 1366 watts per square meter arrive at the outer surface of Earth's atmosphere. On Earth the solar irradiance (power per unit area) is reduced by atmospheric absorption to a value of approximately 1000 watts per square meter. (This is specifically the case at noon near the spring or autumn equinoxes in the continental United States.) Photovoltaic cells utilize approximately 60% of this light. Therefore, a photovoltaic covering an area of one square meter collects approximately 600 watts of light. Using an energy conversion efficiency of 15%, this photovoltaic module can generate 90 watts, enough to run a single light bulb.

The objective in solar power is to convert as much light as possible to electrical power. The previous example showed that the only way to increase the power generated is to cover more area. Fortunately, there is a more cost effective way to increase power generation. This is called *solar collection*.

Solar collection utilizes reflectors or lenses to collect large areas of light and direct them onto smaller photovoltaic modules. In effect, the light that is collected over large areas is squeezed down to fit smaller areas. A simple example would be using a magnifying glass to burn a hole in a leaf. The lens collects light over a large area and redirects it to a focal point. This action increases the power density, watts per area, of the sun's light. The same principle can be utilized in solar power applications.

Concentration ratio

The improvement that can be provided with solar collection devices is expressed as the concentration ratio, C .

$$C = \frac{A_{\text{lens}}}{A_{\text{photovoltaic}}} \quad (5)$$

where A_{lens} is the area of the lens and $A_{\text{photovoltaic}}$ is the area of the photovoltaic cell or module. A concentration ratio of 10 means that the lens is able to collect 10 times more solar energy than would be collected if the photovoltaic cell were used alone.

Lenses for solar collection

A simple positive lens accepts light and changes the angular output by causing the light to converge at a focal point. However, glass lenses can be extremely heavy and expensive to fabricate in large forms. Remember, the objective of solar collection is to reduce the overall cost by decreasing the size of the cell. Rather than thick glass lenses, a special type of lens called a *Fresnel lens* is used (Figure 13).

Fresnel lenses were first used in lighthouses to create beams of light from high-intensity lamps. They consist of annular sections known as *Fresnel zones* that mimic the operation of a much thicker lens. The advantage of a Fresnel lens is that it can be made thin, thus reducing weight. Additionally, Fresnel lenses used for applications such as solar collection can be made of inexpensive materials such as polycarbonate.

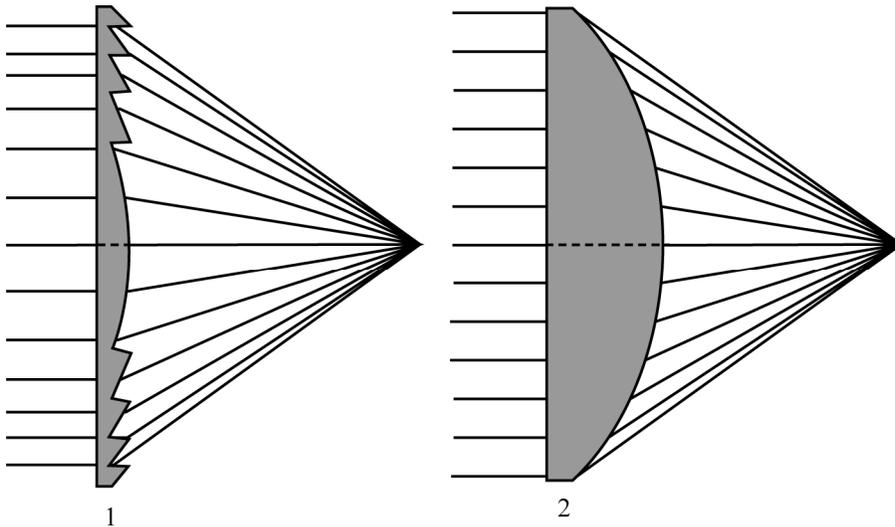


Figure 13 *Fresnel lens (1) compared to planar-convex thick lens (2)*

Fresnel lenses are an economical method for collecting solar power, but they are not currently used in any large solar power operations. They are being used in some new solar energy applications and may be used in future developments. A more traditional method using mirrors is still the preferred solar collection technique.

Reflectors for solar collection

The most common optical device used for solar collection is the *parabolic reflector*. A parabola accepts incident energy from a distant source and directs all of the light rays to a common focal point. This is the same effect that the Fresnel lens has on the light, but the light is reflected rather than bent through refraction. Reflective surfaces have two advantages.

The first advantage of reflectors is that they have uniform reflectance from the UV to the infrared. Reflective surfaces can achieve greater than 95% reflectance over the operating wavelength range of photovoltaic cells (400 nm–1100 nm). In addition, reflective surfaces can be easily coated to protect against environmental conditions. UV light causes polycarbonate Fresnel lenses to degrade over time, thus reducing their transmittance.

The second advantage of reflectors is that they are inexpensive to manufacture in large sizes. Long troughs of parabolic reflectors can be utilized to collect large amounts of solar energy. The thin reflector sheets are also lighter and are easier to move mechanically. This movement, called *tracking*, is covered in the next section.

Tracking

Photovoltaic modules and solar collection systems operate at their maximum performance when aimed directly at the sun. As the sun moves across the sky during the day, best performance can only be achieved if tracking is utilized. Tracking is a mechanical system that calculates the position of the sun based on time and location and then moves the module or collector so that it is pointed directly at the sun. This can be achieved using either a single-axis system or a two-axis system. Single-axis systems move the solar collection device from east to west. This system works well when located near the equator. For non-equatorial installations, a two-axis system is required to maintain the proper angle between the collector system and the sun. This ensures that the sun is almost perfectly directed onto the solar collector, thus maintaining a near-normal angle of incidence. Two-axis systems are more complex and expensive but can aim the solar collector directly at the sun regardless of its location or the time of year.

Compound parabolic concentrators

A parabolic shape can be modified to accept a larger incidence angle. The resulting reflector is called a *Winston concentrator* or more specifically a *compound parabolic concentrator* (CPC). A CPC is formed using two identical parabolas as shown in Figure 14.

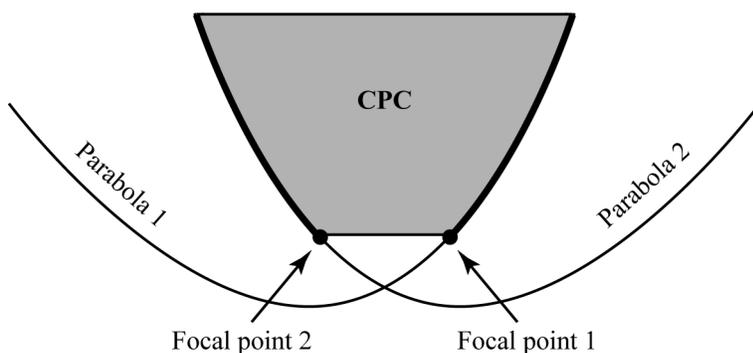


Figure 14 Construction of a compound parabolic concentrator

The focal point of each parabola is positioned on the side of the opposite parabola. This is accomplished by tilting each parabola slightly away from the other. The result is a solar concentrator that can collect the theoretical maximum amount of energy possible, called the *thermodynamic limit*. Figure 15 shows how a CPC is used with a photovoltaic cell. The result is a simple reflector that collects light over a large area and concentrates the light on the

photovoltaic cell, which is placed at the output of the CPC. The advantage of the CPC is that the cell and reflector can remain still while the sun moves across the sky. The CPC will collect light equally well for all angles of the sun within the acceptance angle defined by the lines shown in Figure 15. These lines are drawn from the edges of the entrance aperture to the edges of the exit aperture. Short CPCs will have the widest acceptance angle and long CPCs will have narrow acceptance angles.

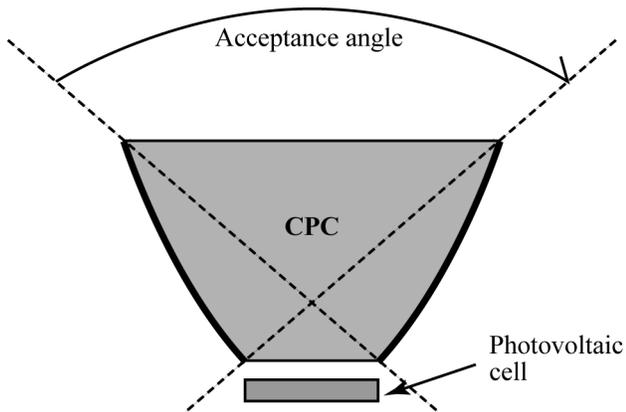


Figure 15 Using a compound parabolic concentrator with a photovoltaic cell

Solar concentrators based on the CPC can be made in trough or circular forms. This is one of the most widely used collection devices.

Electrical Behavior of Photovoltaics

In order to understand how photovoltaics can be applied to various applications, we must first understand their electrical behavior. In this section, the operating current of photovoltaic cells and modules will be explained.

Current and voltage

A photovoltaic cell generates a potential difference or voltage between its contacts when illuminated by the sun. A current flows once the cell is connected to a resistive load. This load represents the system that is being powered by the cell. The operation and performance of a photovoltaic cell is determined by measuring the amount of current with respect to voltage for different amounts of resistance. The plot of all possible cases of resistive loads is called an *I-V curve*. The two extreme load cases are *short-circuit* and *open-circuit*. These cases are both evaluated for strong sunlight equivalent to 1000 watts per meter square.

The short-circuit case occurs when the resistive load is effectively zero ohms. This can be thought of as a single wire connection between the contacts of the cell. This zero-ohm load will cause the cell to generate the maximum amount of amperes possible.

The open-circuit case occurs when the resistive load is infinite. This infinite load is equivalent to disconnecting the cell from any load. In this operation, no current will flow but the maximum amount of voltage potential is generated.

Maximum power

The I-V curve shown in Figure 16 illustrates the operation of a generic photovoltaic cell or module. The short-circuit current, I_{SC} , and open-circuit voltage, V_{OC} , indicate the extreme operating cases. The I-V curve indicates the expected voltage for different currents. The power curve is the product of the current and voltage at each operating voltage. The maximum power point, P_{mp} , is the peak power that the cell can achieve. This power also has a peak current, I_{mp} , and voltage, V_{mp} , corresponding to this maximum power.

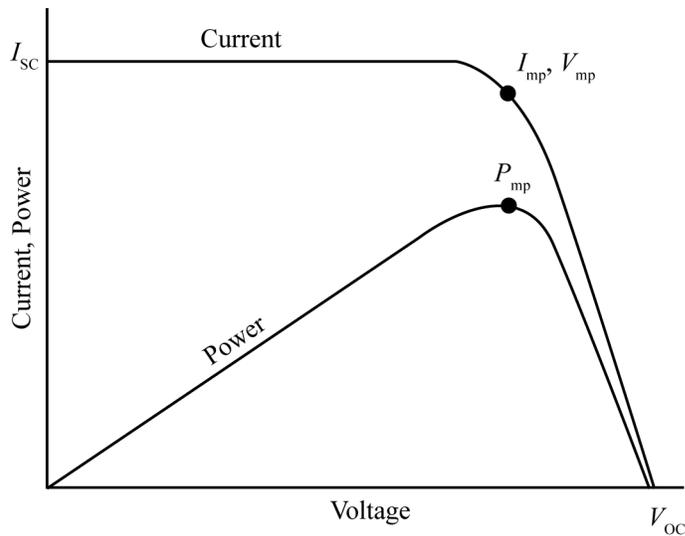


Figure 16 Operating I-V curve for generic photovoltaic cell

The maximum power is usually specified by the manufacturer. The maximum power can also be calculated from two electrical measurements as follows.

Determining maximum power

The maximum power of a photovoltaic cell or module can be calculated using the following expression:

$$P_{mp} = V_{OC}I_{SC}FF \quad (6)$$

The value FF is the fill-factor or effective active area divided by the total area of the cell or module. The effective area is the area of the photovoltaic cell that is capable of converting light to electricity. This value is typically 0.75 or 75%, but the exact value should be available from the manufacturer. Figure 17 is a close-up of a photovoltaic cell showing the finger contacts and effective area.

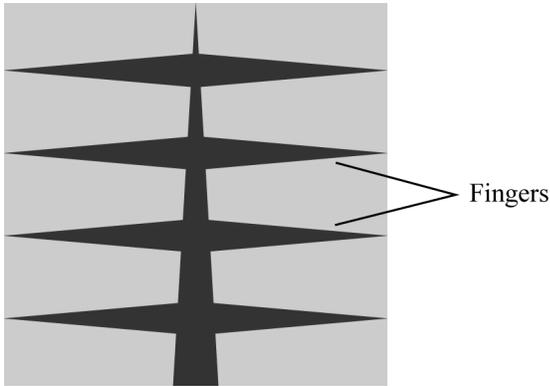


Figure 17 Close-up of photovoltaic showing finger contacts and active area as light grey

The open-circuit voltage, V_{OC} , can be obtained by illuminating the cell or module with strong noontday sunlight. The voltage across the leads of the cell or module is then measured using a standard DC voltage meter. The short-circuit current, I_{SC} , is measured by replacing the voltage meter with an ampere meter (must have a high current rating). These measurements, along with the fill-factor, are used in Equation 6 to calculate the maximum power, P_{mp} .

Example 2: Finding the maximum power of a photovoltaic cell

Given: A photovoltaic cell with a fill-factor of 75% and measured open-circuit voltage of 500 mV and short-circuit current of 2.0 A

Find: Find the maximum power of the photovoltaic cell.

Solution

$$P_{mp} = V_{OC}I_{SC}FF$$

$$P_{mp} = (500 \times 10^{-3} \text{ V})(2.0 \text{ A})(0.75)$$

$$P_{mp} = 0.75 \text{ W}$$

Utilizing Photovoltaic Technology

Photovoltaic technology can be applied to many different applications. In a generic sense, photovoltaics generate electric power that can be used to supplement other means of power generation. In more specific terms, photovoltaics are typically applied to applications where either power is not readily available from other sources or it is cost effective to utilize a solar panel to offset the cost of other sources. A common application is the use of solar panels to recharge battery sources where remote long-term operation is required. An example would be a satellite in orbit around the Earth. In this application, the only power source available would be from a battery. Photovoltaic modules are used in this application to continuously recharge the satellite's on-board bank of batteries. The first step in applying photovoltaic technology is to determine the application's power requirement, also known as *load*.

Determining load requirement

The first step in calculating the load requirement of an application is to determine the needed voltage level of the system. An example would be a farming vehicle such as a tractor that goes unused for varying periods during the year. Without running the tractor, the 12 V battery used to start its engine would decrease in voltage over time. In this example, the needed voltage would be the typical charging voltage of a 12 V automotive battery, which in most cases is 14–14.5 V. This voltage provides the determining factor for the number of cells that must be placed in series to form the module.

The second step in calculating the load requirement is to determine the typical current usage of the system. The required current is used to determine the number of cells that must be used in parallel to form the module.

The maximum current and voltage ratings for a single cell are used to determine the final configuration of the array of cells that will be needed in the module. An example would be an application requiring 18 V and a current of 2.7 A. A typical cell will provide a V_{mp} of 500 mV and I_{mp} of 2.7 A. Therefore, a single series string of 18 V/500 mV or 36 cells would be needed to generate the required 18 V (36 cells \times 0.5 V). If the application called for 18 V with a current of 5.4 A, two parallel strings consisting of 36 cells each would be required. Remember: *Cells in series add voltage and cells in parallel add current.*

Power storage

The ability of solar panels to produce electricity depends directly on the availability of sunlight. Night time and cloudy conditions will cause the power generated to be very low or nonexistent. For this reason, continuously operating applications cannot rely completely on solar power—unless the solar power generated during ideal conditions can be stored for low-yield periods. This is achieved using batteries that can be recharged and drained often.

Several battery chemistries are used for solar power applications. The primary requirement is that electrical energy can be stored as chemical energy. This chemical energy can then be released back into electrical energy. Examples of batteries used in photovoltaic applications are lead-acid, nickel-cadmium, alkaline manganese, lithium-ion, nickel-metal-hydride, and lithium-polymer. The most common type of battery used is lead-acid. This is a mature technology and is relatively inexpensive when compared to technologies such as lithium-ion. Lead-acid batteries are also stable in a wide range of environmental conditions. However, they are heavy compared to batteries with equivalent storage capacity. Still these batteries are used for the majority of land-based applications.

An example application is given in Figure 18, which shows the basic wiring scheme used for recharging batteries. The blocking diode protects the photovoltaic panel from current flowing in the reverse direction. The charge controller governs when solar power is used to recharge the battery.

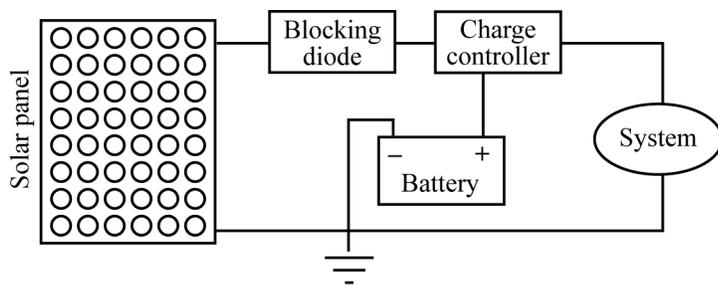


Figure 18 Example solar panel application used to recharge primary battery power source

Applications of Photovoltaics

As photovoltaic technologies become more cost effective, the number of applications will grow exponentially. Currently, solar panels are used to supply power in applications where the resulting performance enhancement surpasses the cost of the panels. Many of these systems require long-term operation in locales where other power supplies are not readily available. An example would be space-based platforms. It is easy to recognize that, in space, power must be continuously generated on-board. In this section, some common applications of photovoltaic technologies will be presented. These types of systems are called *stand-alone photovoltaic systems*.

Marine

Waterway navigation has relied on aides such as floating buoys for many years. These navigation aids operate using various means of communicating their presence to nearby boaters. An example would be mechanically powered bells and whistles. Some buoy designs include lights and electrical sound devices. Traditionally, the electrical sources for these buoys were large banks of batteries periodically replaced by the US Coast Guard. Photovoltaics are now used to continually recharge the primary batteries. This not only reduces the maintenance costs of the buoys but, more importantly to boaters, increases their reliability. In addition, light-emitting diodes (LEDs) have now replaced incandescent bulbs in marine applications, thus reducing power consumption. The long life of LEDs and their reduced power usage have decreased the maintenance costs even greater.

Telecommunication

Long-range terrestrial telecommunication systems utilize signal-boosting repeater stations. For nearly twenty years, one of the primary markets for photovoltaic technologies has been in the remote powering of these repeater stations. In this application, the solar panels are used to recharge the primary batteries. This application of solar energy has been very successful and has enabled communication in harsh terrain that would otherwise not be served.

Water pumping

In many areas of the world, water is obtained from small pumping stations. Traditionally, these stations have relied on wind and diesel engines. Photovoltaics have been used for several years to replace these power sources. The reliability and long lifetime of photovoltaic technology have produced significant advantages. These pumping stations have helped to reduce famine and disease in many developing nations.

Space

Orbiting satellites, planetary probes, and deep-space probes all operate for many years without the ability to connect to terrestrial power supplies (Figure 19). These space vehicles operate continuously, drawing power from banks of onboard batteries. Solar panels are used to continually recharge these battery banks so that the vehicles can continue to operate. In fact, it is hard to imagine building a satellite without including solar panels. The amount of solar energy available in space is fixed at a continuous 1366 watts per square meter except when passing through occluded space. Space platforms do not have to contend with cloudy or otherwise less-than-optimal days. However, the size of the array is governed by the efficiency of the photovoltaic technology used. This is why much current research focuses on improving conversion efficiency for space-based applications. These applications can absorb the expense of high-efficiency panels since payload weight is the dominating cost.

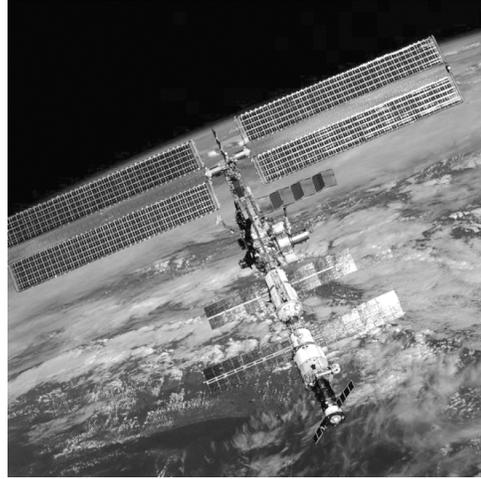


Figure 19 *Solar panel powers the International Space Station (courtesy of NASA)*

Residential

The rising cost of residential power has caused many consumers to turn to solar power to supplement their energy supply. The initial cost of the needed solar panels is still seen as a barrier for this market. Still, some consumers have made the investment because the long-term savings can be sizable. The panels are typically mounted on the roof of the residential structure. The power generated by the array of panels is then tied into the internal power grid of the dwelling. Figure 20 shows one of the first solar houses.



Figure 20 MIT solar house (circa 1940)

Commercial utility-scale generators

There are several large installations of solar-based power generation. These are called grid-connected applications since the electrical power generated is fed into the regional power grid for residential and commercial buildings. These installations utilize hundreds or even thousands of photovoltaic panels to generate megawatts of electrical power.

EXERCISES

1. Over what wavelength range can silicon-based photovoltaic cells be used?
2. What is the power density of solar irradiance on the outer surface of the atmosphere in watts per square meter?
3. What is the maximum power point of a photovoltaic panel with a fill-factor of 75%, short-circuit current of 1.8 A, and open-circuit voltage of 600 mV?
4. If a single photovoltaic cell can generate 1.0 A and a voltage of 1 V, what configuration of cells would be needed for a 10 V application for 100 W power generation?
5. What is the reflection loss of a photovoltaic cell if the index of refraction is 4.0 for the base silicon material?
6. How can the reflection loss in a photovoltaic cell be minimized?
7. What type of reflector increases the useful angular input to a photovoltaic cell?
8. What is a common application of solar panels?
9. What is the energy of a photon at a wavelength of 450 nm?
10. If the energy gap of a material is 1.8 eV, what is the cut-off wavelength of the material?

LABORATORY

The laboratory procedures presented here require the use of standard photovoltaic cells and electrical measurement equipment. The needed materials are listed below.

Materials

Encapsulated high-output solar cells (Edmund Scientifics Item # 30034063)
Digital voltmeter/ammeter
Hookup wire (18gauge)
MR16 tungsten halogen 120 V AC desk lamp

Procedure 1: Measurement of maximum power

1. Place a single cell beneath the halogen desk lamp approximately 1 foot away.
2. Connect the voltmeter between the leads of the cell. Record this measurement in the table.
3. Switch the voltmeter to current measurements, making sure that the meter is rated for at least 1 A maximum current. Record this measurement in the table below.
4. Use the formula below with a fill-factor, FF , of 75%.

$$P_{mp} = V_{OC}I_{SC}FF$$

5. Complete this measurement for 8 cells.

Cell 1	
Parameter	Measurement
Open Circuit Voltage	
Short Circuit Current	
Calculated Maximum Power	

Cell 2	
Parameter	Measurement
Open Circuit Voltage	
Short Circuit Current	
Calculated Maximum Power	

Cell 3	
Parameter	Measurement
Open Circuit Voltage	
Short Circuit Current	
Calculated Maximum Power	

Cell 4	
Parameter	Measurement
Open Circuit Voltage	
Short Circuit Current	
Calculated Maximum Power	

Cell 5	
Parameter	Measurement
Open Circuit Voltage	
Short Circuit Current	
Calculated Maximum Power	

Cell 6	
Parameter	Measurement
Open Circuit Voltage	
Short Circuit Current	
Calculated Maximum Power	

Cell 7	
Parameter	Measurement
Open Circuit Voltage	
Short Circuit Current	
Calculated Maximum Power	

Cell 8	
Parameter	Measurement
Open Circuit Voltage	
Short Circuit Current	
Calculated Maximum Power	

6. Calculate the average voltage, current, and power

Parameter	Average Value
Open Circuit Voltage	
Short Circuit Current	
Maximum Power	

Procedure 2: Series Array

1. Connect all eight of the cells in series, twisting wires together by hand.
2. Take the system outside in clear weather.
3. Measure the voltage across the first and last cells.

4. Measure the current across the first and last cells.
5. Calculate the maximum power as in Procedure 1.

Parameter	Series Value
Open Circuit Voltage	
Short Circuit Current	
Maximum Power	

Procedure 3: Parallel Array

1. Disconnect the series array in the middle, leaving two strings of four cells in series.
2. Connect the two strings in parallel.
3. Measure the voltage across the first and last cells.
4. Measure the current across the first and last cells.
5. Calculate the maximum power as in Procedure 1.

Parameter	Parallel Value
Open Circuit Voltage	
Short Circuit Current	
Maximum Power	

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