

The Photovoltaic Challenge

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Solar Energy

The term "solar energy" refers to a wide variety of techniques for using the energy available as sunlight. Well-known examples are active and passive thermal solar energy and photovoltaic solar energy but, strictly speaking, hydropower, wind energy, and biomass are also forms of solar energy. Today, only hydropower is used in significant quantities, covering approximately 6% of the world's energy demand¹. Traditional use of biomass, mainly in developing countries, accounts for more than 10% of the total energy consumption^{1,2} but is sometimes left out of statistics because it falls outside the category of organized and commercial use.

The global potential for solar energy is huge, since the amount of energy that reaches the earth's surface every year exceeds the total energy consumption by roughly a factor of 10,000. There are, however, various barriers to the large-scale use of solar energy technologies. Most technologies have in common that the power density of the generator is low; in other words, one needs large areas to generate significant amounts of energy. This is especially true for biomass, with typical conversion efficiencies (solar energy to chemical energy) of 1% or less. Further, many solar energy technologies have proved technically feasible, but have yet to be proved economically feasible. Last, but not least, the large-scale use of solar energy requires substantial modification of our global energy supply system, which is based largely on fossil fuels.

Fortunately, these disadvantages are offset by the intrinsic advantages of solar energy. Overall emissions of CO₂ and other gases (for instance, those associated with the construction of solar hardware) are generally small because no fuel is used during operation. In addition, solar energy, if used correctly, is a renewable source of energy which can be used indefinitely. Finally, it can be made available in some form to people in almost all areas of the world.

Photovoltaics

Among the solar energy technologies, the modern use of biomass through energy plantations, and photovoltaic solar energy (PV) have been identified as rapid-growth technologies with a very large potential.¹ A PV system is a modular, fully solid-state electricity generator (see Figure 1). It is therefore reliable and can be used in many different applications, varying from calculators and stand-alone Single or dual-module solar home systems³ (see Figure 2) to grid-connected roof-integrated systems (see cover photo) and central power plants. A major obstacle to large-scale use of PV is the high initial investment cost. Typical electricity generation costs are between US \$0.25 and \$1.00 per kWh for different types of systems and different locations. As a result, the use of PV is limited mainly to applications in which electricity is given a high value or where a clean, quiet, and reliable generator is needed. This is the case, for example, in remote areas (rural electrification, telecommunication, water pumping recreation, etc.) and in areas with a weak grid or high peak loads (peak shaving). Total 1992 sales of PV systems were roughly 60 MWp (megawatt peak, where 1 megawatt peak of PV-modules is the amount that delivers 1 MW of electric power under standard illumination conditions (1,000 W/m², 25 or 28 °C)). The market is expected to expand enormously when electricity from PV can be fed into the public grids at costs that are comparable to generation costs of electricity from fossil fuels. This break-even point can be reached only if the total PV system costs are reduced significantly, although it will be of great help to PV and other renewables if societal costs of energy are taken into account in the comparison between different generation technologies.⁴

For this reason, scientists and engineers throughout the world are working on the development of PV systems with a better cost/performance ratio. This is done by increasing the efficiency of cells and modules, by reducing their cost, or both, and by improving the other system components such as mechanical support (including integration techniques), regulators, dc/ac inverters, batteries, etc. It is noted that apart from technological improvement, scaling up of production is a prerequisite for realizing low cost.

This issue of the MRS Bulletin is meant to give an overview of the different approaches used for developing improved cells and modules.

Solar Cells

The operation of solar cells is based on the photovoltaic effect, that is the generation of a voltage and/ or a current by absorption of light in some material or combination of materials (for excellent reviews, see References 1 and 5). Figure 3 gives a cross section of a simple solar cell structure. It consists of a sandwich of p-type and n-type material separated by a p-n junction, with electrical contacts on front and back. The thickness of this sandwich may vary from less than a micron for strongly absorbing (direct bandgap) semiconductors to a few hundred microns for a weakly absorbing (indirect bandgap) Semiconductor-like crystalline silicon. Upon absorption of a photon in the

semiconductor, an electron-hole pair is created. At the p-side, electrons are minority charge carriers and holes are majority carriers (n-side vice versa). Electrons and holes have to be separated spatially and collected in order to use the energy that each pair represents. To achieve separation, the minority carriers have to diffuse to the junction, where they will be swept away by the built-in electric field. In open-circuit conditions, this process will lead to the buildup of a potential difference V_{OC} between front and back, in short-circuit conditions to a current I_{sc} between front and back. Maximum power P_{max} is obtained for a specific combination of voltage and current, i.e., for a specific load (see Figure 4). In a module with cells connected in series, this set point is maintained electronically by a maximum power point tracker (MPPT) or imposed by the charging voltage of a battery.

Although the overall behavior of many solar cells can be understood from the simplified model described in the previous paragraph, it is useful to mention two other approaches used in solar cell design. First, in some types of solar cell (e.g., amorphous silicon cells—see article by Hamakawa et al. in this issue), the main absorption region is not doped, but composed of undoped (intrinsic) semiconductor material. In these p-i-n cells, electrons and holes are separated by drift rather than diffusion (see Figure 5). Second, in the recently developed dye-sensitized cells, the functions of light absorption and charge transport are entirely separated (see article by Gratzel in this issue).

Efficiency

The efficiency of a solar cell, defined as the ratio of the maximum electric power and the power of the incident light, is usually determined under standard test conditions of 1,000 W/m² illumination and 25°C. The spectral distribution of the light is expressed in terms of an optical air mass (AM) number. AM0 corresponds to the spectrum in space, AM1 to the spectrum at the earth's surface when the sun is overhead, AM2 when the sun is 60° off overhead, etc. (idealized cases). Cells and modules for terrestrial use are generally measured under AM1 or AM1.5 conditions. The efficiency of solar cells is determined by many factors, but some represent fundamental limitations, while others can be influenced by the technology used. Many attempts have been made to calculate the efficiency limit of a solar cell and, although results vary, most authors arrive at values between 25% and 30% for single-bandgap (approximately 1.1-1.4 eV) cells under natural sunlight. More than two-thirds of the total losses in such an ultimate cell are associated with spectral mismatch (light of different wavelengths, one bandgap for absorption), while the remaining part is due to the recombination of charge carriers and, to a smaller extent, reflection, resistance, etc. For multibandgap (tandem) structures and/or operation under concentrated sunlight, much higher efficiency values are calculated (35% and up). Some important experimental record efficiencies are 23% for a single-crystal silicon cell, 18% for a multicrystalline silicon cell, 13% for an amorphous silicon cell (all under natural sunlight), and 35% for a GaAs/ GaSb tandem cell under concentrated light (see elsewhere in this issue).

Commercial module efficiencies are considerably lower than the record numbers for cells, namely less than 15%. This is due to differences in size (approximately 0.4 m² versus a few cm²), to differences in cell design, technology and material, and to the use of average efficiencies (modules) rather than record efficiencies (cells). Obviously, optimizing a commercial module does not imply simply maximizing the efficiency, but rather finding the optimum combination of efficiency and cost. Nevertheless there remains room for substantial improvement of module efficiencies and it is expected that modules with efficiencies in the 18-20% range will become available within the next decade. Ultimately, modules based on tandem technology will probably reach efficiencies of 30-40%.

Materials for Photovoltaics

The number of materials considered for the fabrication of solar cells and modules is already large and still growing. The original choices were motivated mainly by material availability and processing possibilities, but the recent boost in interest for PV has also triggered a more systematic search for new materials and cell structures that may (also) fulfill the ultimate requirements of efficiency, cost, stability, and environmental effects. The articles in this issue cover the whole range from well-known and very advanced technologies, through emerging thin-film technologies, to truly new technologies. They deal, therefore, with R&D aimed at short- or mid-term application, as well as with fundamental work. The character of the articles reflects this difference in scope. Although the over

view is not complete, most of the materials and approaches considered important today are included. They are dealt with by well-known experts and pioneers. In order of appearance, the materials are:

- (1) single-crystal silicon,
- (2) cast multicrystalline silicon (also referred to as (cast) polycrystalline silicon or semicrystalline silicon),
- (3) thin-film polycrystalline silicon,
- (4) amorphous silicon,
- (5) copper indium diselenide,
- (6) cadmium telluride,
- (7) gallium arsenide,

(8) multiquantum wells,
(9) iron sulfide; and
(10) nanocrystalline (dye-sensitized) thin films.
(1) and (2) represent the mature crystalline silicon technologies already available today, (3) is about a new way of preparing and using crystalline silicon, (4) deals with the thin-film material that most people know from calculators but that has a lot more to offer, (5) and (6) are about emerging thinfilm technologies, (7) and (8) discuss two distinctly different high-efficiency approaches, while (9) and (10), finally, are about new "super-low-cost" thinfilm options.

How a Solar Cell Works

The photovoltaic effect is the basis of solar-cell technology. The key to this effect is a semiconductor, the same type of material used in the transistors and diodes that have replaced nearly all the tubes and switches in electrical products. Under normal conditions, a semiconductor behaves electrically like an insulator that inhibits the transfer of electrical energy. An external stimulus of sufficient energy causes these materials to act like electrical conductors, however, with little resistance to the transfer of electrical energy. Sunlight is the external energy source in photovoltaic devices. Thus, when sunlight illuminates semiconductor PV materials, they respond by becoming conductors of electric current.

Photovoltaic devices act not only as conductors of current but also as current generators. This occurs when two slightly dissimilar semiconductors are placed in contact. A potential energy barrier is formed that acts like a battery. Therefore, when sunlight strikes a PV device (two or more semiconductors in contact), there can be current flow because of the electric potential.

Connectors are attached to the two semiconductors to conduct current. These are usually in the form of (1) a grid on the top surface, to maximize contact and minimize the obstruction of sunlight, and (2) a thin coating on the back. Besides the references quoted here, several books on residential PV provide good overviews on how a cell works: *Solar Electric House*, by Steven Strong, Rodale Press; and *The New Solar Electric House*, by Joel Davidson, Water Publications.

There are several ways to form a potential barrier (also called a junction) in a crystalline silicon solar cell. One is to alter the material composition by adding desired impurities to replace some of the silicon. Silicon atoms have four electrons. One layer of the silicon is doped with atoms having five outer electrons. Since each donor atom shares four of its outer electrons with four neighboring silicon atoms, one unattached electron is left free to roam the crystal. The donor-doped layer is referred to as n-type silicon because of the excess free negative charges.

The other layer of silicon is doped with atoms having three outer electrons. Each of these atoms shares its three valence electrons with three neighboring silicon atoms, but since there are four neighboring silicon atoms needing to share electrons, an extra bond is left available with no electron to fill it, and this results in an excess of holes. This layer is known as p-type silicon because of the excess free positive charges.

The two differently doped layers are joined, forming a p-n junction at their common surface. This type of photovoltaic device is also called a homojunction solar cell, because it joins semiconductor materials of the same substance. Once joined, free negative particles from the n-type silicon cross the p-n junction to fill up holes near the junction on the p-type side, while free holes from the p-type side cross over to the n-type side. This exchange of charges causes a charge imbalance, with excess positive charges on the n-type side and excess negative charges on the p-type side. Eventually, equilibrium occurs when the charge imbalance gets large enough to set up a force repulsing other free charges from crossing the junction. This repulsive force (or potential barrier) remains a somewhat stable and permanent characteristic of the cell. When sunlight strikes the cell and knocks electrons loose from their bonds, the barrier separates the charges, setting up a potential voltage. This voltage drives a current (composed of the electrons freed by sunlight) through electrical contacts attached to each layer of the cell, and then through an external circuit. A typical crystalline silicon photovoltaic cell produces a maximum characteristic voltage of about 0.5 V.

Many books, reports, and articles provide information on the theory behind solar cell operation, especially the publications listed in Chapter 1. The publications cited here go into much greater detail on physics and chemistry of photovoltaics and the design of solar cells.

Solar Radiation and Photovoltaics

The output of photovoltaic cells is affected by both the intensity and the spectral distribution of sunlight. The sun is an immense power source emitting a large amount of electromagnetic energy in the form of light. Though this type of energy is similar to radio and TV signals, its wavelength is much shorter. Each wavelength has a different level of energy and may be visible or invisible. The color of light is determined by its wavelength; "white" sunlight is made up of many different colors.

Solar cells respond differently to different wavelengths, or colors, of light. Crystalline silicon can utilize the entire visible spectrum as well as some part of the infrared spectrum. Energy in some part of the infrared spectrum and longer-wavelength radiation are not sufficient to produce current flow. Higher-energy radiation can produce current flow, but much of this energy is also not usable. When the energy that is too high or low hits the cell, it is transformed to heat and the cell becomes hotter.

Of the enormous amount of power generated by the sun, only a small fraction reaches the earth's surface. The earth's atmosphere and clouds absorb and reflect some of the sunlight, and dust particles scatter some of the light. The result is that only 1000 W/m^2 of light is available at the earth's surface when the sun is shining directly overhead, and approximately 1350 W/m^2 occurs at the outside edge of the earth's atmosphere.

This change (or loss of energy) depends on the amount or thickness of the atmosphere that the sun's energy must pass through. The radiation that reaches sea level at high noon in a clear sky (providing 1000 W/m^2) is described as air-mass-one (AM1) radiation. As the sun moves lower in the sky, sunlight passes through greater amounts of air—losing more energy. Because the sun is overhead for only a short time, the air mass is normally greater than one; i.e., the available energy is less than 1000 W/m^2 . The amount of energy from the sun also changes with the seasons. The actual amount of sunlight falling on a specific geographical location is known as insolation.

Insolation data for a specific site is sometimes difficult to obtain. Weather stations, equipped to measure the necessary solar radiation components, are located far apart and seldom carry specific insolation data for a given site. Furthermore, the information most generally available is the average daily total (or global) radiation on a horizontal surface. Global sunlight is made up of two parts: direct-normal sunlight (about 80% of the total) that comes straight from the sun, and diffuse sunlight, the light that is reflected off clouds, the ground, or other objects. Diffuse and direct-normal sunlight generally have different spectra (distributions of color).

The most comprehensive and widely used insolation data are being collected by the National Climatic Data Center in Asheville, North Carolina. The Resource Assessment Branch of the Solar Energy Research Institute has also been instrumental in gathering solar radiation data of particular interest to PV researchers and system designers.

Factors that Affect the Efficiency of Solar Cells

Most of the energy that reaches a photovoltaic cell in the form of sunlight is lost before it can be converted into electricity. The best single-junction PV devices have theoretical maximum power conversion efficiencies ranging from 20% to 28%, depending on the material. The practical limit is generally lower. The highest efficiencies of experimental cells in 1987 were almost 24% under unconcentrated light. Certain characteristics of semiconductor materials limit a cell's efficiency. Although some of these characteristics are inherent and cannot be changed, many can be improved by selecting appropriate materials and designing the cell carefully.

When light composed of photons at a range of wavelengths strikes the surface of a semiconductor, it loses a fraction of its photons by reflection from the surface. Some photons pass through the material, some become absorbed (but only have enough energy to generate heat), and some are capable of separating electrons from their atomic bond (producing electron-hole pairs).

The minimum amount of energy necessary to free an electron from its bond (called the band gap) varies with different semiconductor materials. The chief reason why PV cells cannot achieve 100% efficiency is that they are unable to respond to sunlight's entire, wide spectrum. Photons whose energy is less than that of the material's band

gap are not absorbed, which is a waste of about 25 % of the incoming energy. The energy content of photons above the band gap will be wasted surplus, re-emitted as heat or light; this accounts for an additional loss of about 30%. The inefficient interactions of light with the cell material thus waste about 55% of the energy from the original sunlight. Some advanced solar-cell technologies, such as multijunction cells, contain several different semiconductor materials with a range of band gaps; this means that more of the incoming light, at more wavelengths, can be absorbed.

Another factor that limits cell efficiency is the inadvertent recombination of electrons and holes before they can contribute to an energy current. Direct recombination, in which light-generated electrons and holes randomly encounter each other and recombine, is the major problem in some solar-cell materials. In others, indirect recombination is the dominant problem. Indirect recombination occurs when electrons or holes encounter an impurity, a defect in the crystal structure, a surface, or a similar disturbance that makes it easier for them to recombine.

The natural resistance to electron flow in a cell also decreases cell efficiency. These losses occur predominantly in three places: in the bulk of the base material, in the narrow top-surface layer typical of many cells, and at the interface between the cell and the electric contacts leading to an external circuit.

Cell efficiency is also affected by temperature. Solar cells work best at low temperatures, as determined by their material properties. All cell materials lose efficiency as the operating temperature rises. Since so much of the light energy incident on cells becomes heat, it is Advantageous to either match the cell material to the temperature of operation or to continually cool it. In some cases, removing excess heat from the PV cells can actually raise the system's overall efficiency. The unwanted heat may be used for thermal applications.

Another way to increase cell efficiency is to minimize the amount of light that is reflected away from the cell's surface. Untreated silicon reflects more than 30% of incident light; test results from many other PV materials reveal similar problems. Various antireflection (AR) technologies have been developed to optimize light absorption. The most common strategy is to apply a special coating to the top layer of the cell. A single AR layer will effectively reduce reflection only at one wavelength; better results, over a wider range of wavelengths, are possible with multiple AR layers. Another way to reduce reflection is to texture the top Surface of the cell, which causes reflected light to strike a second surface before it can escape, thereby increasing the probability of absorption. If the front surface is textured into pyramid shapes for antireflection, this bends all the incident light so that it obliquely strikes the polished (but otherwise untreated) back surface of the cell. This type of texturing causes light to be reflected back and forth within the cell until it is completely absorbed.

Another problem in solar-cell design is electrical resistance. Larger electrical contacts can minimize resistance, but covering a cell with large, opaque metallic contacts would block out too much light. Therefore, a trade-off must be made between resistance losses and shading effects.

Typically, top-surface contacts are designed as grids, with many thin, conductive fingers spread out on the cell's surface. It is difficult to fabricate a grid that maintains good electrical contact with a cell while simultaneously resisting the deterioration caused by fluctuations in temperature or humidity. The back-surface contact to a cell is generally not as complex, often simply a metal sheet. New grid designs, such as those placed only on the cell's back surface or made of transparent grid materials, are being investigated to overcome some of these problems.

The design of photovoltaic cells varies to counteract the limitations in the cell material. The four basic designs are homojunction cells (such as crystalline silicon), heterojunction cells (such as CuInSe_2), p-i-n cells (such as amorphous silicon), and multijunction combinations of these structures.

Homojunction Devices

In designing a homojunction cell, described at the beginning of this chapter, several different aspects of the cell and its junction can be varied to increase efficiency: the depth of the potential barrier below the Surface of the cell; the amount and distribution of dopant atoms on either side of the barrier; and the crystalline quality and purity of the silicon. A thin layer of an insulating material between the metal contacts and the top semiconducting layer can also help increase efficiency.

An innovative design for homojunction cells is currently being developed for use in concentrators. The design entails placing the positive and negative electrical contacts on the back of the cell. This has the advantage of eliminating the shadowing caused by the electrical grid on top of the cell. Its disadvantage is that the charge carriers, which are mostly generated near the top surface of the cell, then have to travel farther—all the way to the back of the cell—to reach an electrical contact. If the charge carriers are to do that successfully, the silicon must be extremely good quality, that is, be free of the crystal defects that can cause charge carriers to recombine.

Two principal types of back-contact cells are being developed: the point-contact cell, in which electrical contacts form a pattern of small (about 6-micron) dots, and the interdigitated back-contact cell, in which the electrical contacts resemble long fingers, with positive and negative fingers on the back.

Heterojunction Devices

Other PV cell materials and designs employ a heterojunction. These are structures in which the junction is formed between semiconductors that have different energy band gaps. Heterojunction devices have an inherent advantage over homojunction devices. Homojunction devices—structures that use only a single semiconductor material to form the junction—require materials that can be doped both p- and n-type. Many PV materials can be doped p- or n-type, but not both. Consequently, heterojunctions allow us to use many promising PV materials that might otherwise be excluded.

The top and bottom layers in a heterojunction device have different roles. The top layer, or window, is a material with a wide band gap selected for its transparency to radiation. The window can allow almost all the incident light to reach the bottom layer, which is a low-band-gap, highly absorbent material. The light then generates electrons and holes very near the junction, which helps to effectively separate the electrons and holes before they recombine. The window-absorber design also reduces recombination at the top surface of the cell, because very few minority carriers are generated in the top (window) layer.