PHOTOVOLTAIC CELLS

A photovoltaic (PV) solar power system is a complete electrical source that uses solar cells to directly convert light energy into electricity. The system can be self-contained and completely autonomous or it can work in tandem with other conventional fuel-based sources of power to offer robust power availability.

A solar cell is a semiconductor device that can convert light instantaneously into direct-current (d-c) electricity. A number of cells are typically connected together in series in a weather-resistant package such that enough voltage is generated to recharge a 12-volt lead–acid storage battery, the most common storage device used in conjunction with solar power (see BATTERIES, LEAD–ACID). Such a package of cells is designated a PV module, which is often constructed of an external sheet of strengthened glass and polymeric encapsulation. The most common size module is 0.5–1 m² in area and delivers between 25 and 150 watts of power.

The advantages of photovoltaic cells as a source of electric power over alternative power sources may be characterized as follows: solar cells capture sunlight, an essentially inexhaustible and nonpolluting energy source which is freely distributed, and directly convert that light into electricity; photovoltaic generation of electricity requires no machinery with moving parts and produces no noise, waste, or polluting by-products; photovoltaic systems are modular and therefore can be adapted for a variety of applications. Solar power systems are particularly useful in areas where power lines cannot be readily or inexpensively routed.

Solar cells have been used extensively and successfully to power satellites in space since the late 1950s, where their high power-to-weight ratio and demonstrated reliability are especially desirable characteristics. On earth, where electrical systems typically provide large amounts of power at reasonable costs, three principal technical limitations have thus far impeded the widespread use of photovoltaic products: solar cells are expensive, sunlight has a relatively low power density, and commercially available solar cells convert sunlight to electricity with limited efficiency. Clearly, terrestrial solar cells must be reasonably efficient, affordable, and durable. International efforts are dedicated to obtaining such devices, and a number of these activities have been reviewed (1).

The power density of sunlight is about 1350 W/m² at elevations just above the earth's atmosphere (2). Less than 1000 W/m² is typically incident on earth after filtering through the atmosphere. For comparison, in every four clear daylight hours on earth, energy from the sun that falls on an area the size of a large car is equivalent to that stored in 3.8 L (~1 gal) of gasoline. That amount of gasoline will produce about 10 kWh of electrical output if consumed in a conventional power plant. The conversion efficiencies, which theoretically can be attained from the most efficient cell materials, are 25–40% under standardized test conditions, but typical cell performance falls below these limits. The conversion efficiency of a solar cell is the ratio of electric power output to solar power input. Due to the low power density of sunlight and limited conversion efficiencies, the most efficient solar modules can generate about 250 W/m² in peak sunlight conditions. The maximum power output of a solar cell or module is defined in peak watts (W_{peak}), a rating based on a standard measurement method established by international consensus. A solar panel of one square meter area nominally produces one kilowatt hour of electricity per day. For most large-scale, power-producing applications, solar modules have conversion efficiencies above 10% in order to minimize the total cost of a generating system.

Chemistry

Crystalline silicon p–n junction solar cells are the principal commercially available type and are used here to illustrate the operation of a solar cell. When sunlight falls on a solar cell, a voltage is induced and an electric current flows in an external circuit that is connected to the cell. Each atom in the silicon crystal lattice is surrounded by and bound to four equidistant neighboring atoms. The outermost shell of electrons of each silicon atom contains four valence electrons, and each of the four valence electrons in the crystal lattice is shared in a bonding orbital with an electron from one of its four nearest neighbors. This electron pair or covalent bond firmly binds the crystal. If all the valence electrons were inexorably bound, as they would be at 0 degrees kelvin, the silicon crystal would be an insulator because no free electrons would be available, and conduction would be precluded (Fig. 1a). However, the covalent bonds can be broken, eg, by thermal excitation (Fig. 1b). The energy required to break a covalent bond is the bond energy or energy gap, E_g. In silicon, E_g is ca 1.1 eV.
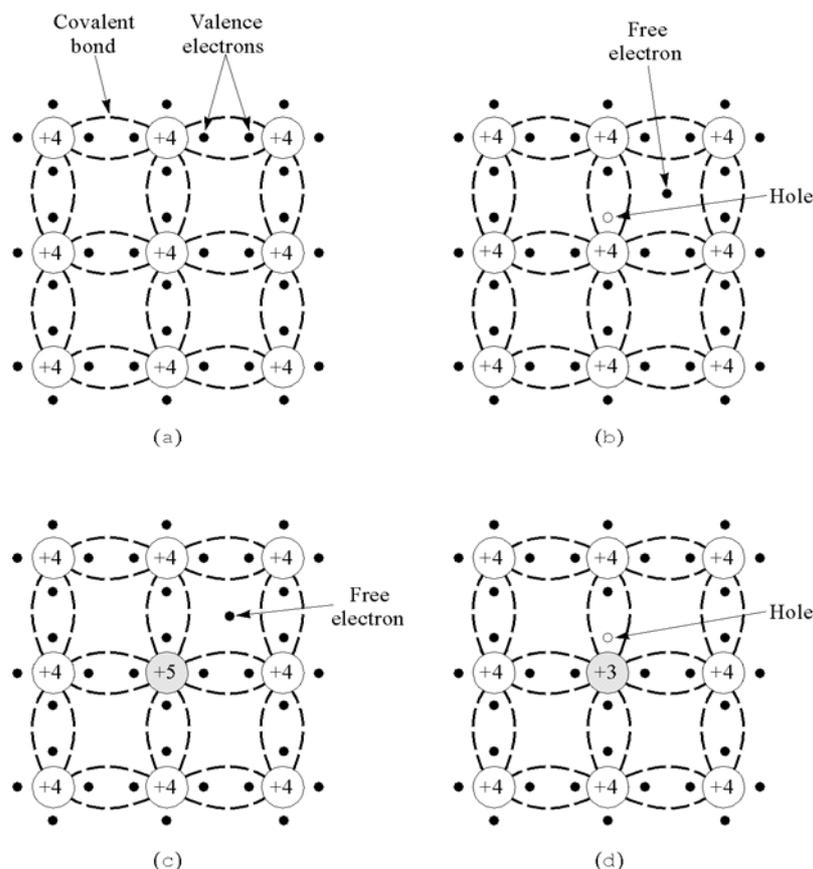
Fig. 1. (**a**) Silicon (valence = 4) crystal lattice shown in two dimensions with no broken bonds, $T = 0$ K; (**b**) silicon crystal lattice with a broken bond; (**c**) silicon crystal lattice with a silicon atom displaced by a donor dopant, ie, *n*-doped (valence = 5); and (**d**) silicon crystal lattice with a silicon atom displaced by an acceptor dopant, ie, *p*-doped (valence = 3).

The absence of an electron from a covalent bond leaves a hole and the neighboring valence electron can vacate its covalent bond to fill the hole, thereby creating a hole in a new location. The new hole can, in turn, be filled by a valence electron from another covalent bond, and so on. Hence, a mechanism is established for electrical conduction that involves the motion of valence electrons but not free electrons. Although a hole is a conceptual artifact, it can be described as a concrete physical entity to keep track of the motion of the valence electrons. Because holes and electrons move in opposite directions under the influence of an electric field, a hole has the same magnitude of charge as an electron but is opposite in sign.

The energy in light also can break the bonds of silicon valence electrons. Each photon has energy equal to the product of Planck's constant and the frequency of the light, ie, $E = h\nu$, where E is photon energy, h is Planck's constant, and ν is the frequency of light. Solar photons range in energy from 0.5 eV for infrared to 4 eV for ultraviolet.

When a photon having energy equal to or greater than E_g is absorbed by the silicon crystal, the photon breaks a covalent bond, thereby freeing an electron and forming a hole. An electron is excited by a photon from a valence-energy band in a covalent bond into a conduction-energy band. The electron, which is transformed into a mobile, negatively charged carrier, leaves behind a mobile hole and consequently the photon has formed a free electron–hole pair.

If the hole and electron are not kept apart, they recombine to produce a small amount of thermal energy within the crystal and no net current flow. When the holes and electrons are kept apart, collected, and made to flow in a circuit outside the crystal, they produce electric current in that circuit. Solar cells are equipped with a barrier or a junction which provides an internal electric field that segregates photogenerated electrons and holes. Thus, although unmodified silicon has an equal number of holes and electrons, a *p–n* junction silicon solar cell consists of two charge-dissimilar regions which are separated by a junction: one region is rich in holes (positive), ie, *p*-type silicon, and the other is rich in electrons (negative), ie, *n*-type silicon. Such regions do not occur naturally; they are fabricated by doping, ie, replacing some silicon atoms in the lattice with atoms having a valence other than four. Replacement of a few silicon atoms, ie, ca one in several million, causes large increases in the electrical conductivity of the resultant doped crystal.

Atoms of elements that are characterized by a valence greater than four, eg, phosphorus or arsenic (valence = 5), are one type of dopant. These high valence dopants contribute free electrons to the crystal and are called donor dopants. If one donor atom is incorporated in the lattice, four of the five valence electrons of donor dopants are covalently bonded, but the fifth electron is very weakly bound and can be detached by only ca 0.03 eV of energy. Once it is detached, it is available as a free electron, ie, a carrier of electric current. A silicon crystal with added donor dopants has excess electron carriers and is called *n*-type (negative) silicon (Fig. 1c).

When a silicon crystal is doped with atoms of elements having a valence of less than four, eg, boron or gallium (valence = 3), only three of the four covalent bonds of the adjacent silicon atoms are occupied. The vacancy at an unoccupied covalent bond constitutes a hole. Dopants that

contribute holes, which in turn act like positive charge carriers, are acceptor dopants and the resulting crystal is *p*-type (positive) silicon (Fig. 1**d**).

Conductivity in doped silicon crystals is determined by the properties of the added charge carriers or majority carriers. In *n*-type silicon, electrons are majority carriers and holes are minority carriers. There are fewer holes in *n*-type silicon than in undoped silicon because the large number of electrons causes some recombination with preexisting holes. In *p*-type silicon, holes are the majority carriers and electrons are the minority carriers. Fewer electrons are present in *p*-type silicon than in undoped silicon because of the recombination of some electrons with the enhanced population of holes.

Junctions

Four different types of junctions can be used to separate the charge carriers in solar cells: (*1*) a homojunction joins semiconductor materials of the same substance, eg, the homojunction of a *p–n* silicon solar cell separates two oppositely doped layers of silicon; (*2*) a heterojunction is formed between two dissimilar semiconductor substances, eg, copper sulfide, Cu_xS, and cadmium sulfide, CdS, in Cu_xS–CdS solar cells; (*3*) a Schottky junction is formed when a metal and semiconductor material are joined; and (*4*) in a metal–insulator–semiconductor junction (MIS), a thin insulator layer, generally less than 0.003-μm thick, is sandwiched between a metal and semiconductor material.

Fabrication methods that are generally used to make these junctions are diffusion, ion implantation, chemical vapor deposition (CVD), vacuum deposition, and liquid-phase deposition for homojunctions; CVD, vacuum deposition, and liquid-phase deposition for heterojunctions; and vacuum deposition for Schottky and MIS junctions.

A homojunction can be made on a silicon wafer in the following ways. In the solid-state diffusion process, a *p*-type wafer is heated to a high temperature (ca 850°C) and is placed in contact with the vapor of a desired *n*-type dopant, eg, $POCl_3$ or PH_3. The dopant atoms thermally migrate or diffuse into the wafer. The dopant concentration converts the top surface layer of the wafer into a *n*-layer, thus forming a *p–n* junction. The *n*-type dopant can be ionized in a vacuum and the ions accelerated to high velocities and injected into the surface of a *p*-type wafer (ion implantation) to form the *p–n* junction. Alternatively, the *p–n* junction can be formed by growing a thin *p*-type layer of silicon on a *n*-type wafer using various techniques. In chemical vapor deposition, a gas that contains a silicon compound and a *p*-dopant is decomposed on the surface of a *n*-type wafer, generally at atmospheric pressure, to form a thin, doped silicon layer. During vacuum deposition, vaporized silicon and *p*-dopant atoms are deposited on the *n*-type wafer in a vacuum. In liquid-phase deposition, the *p*-type layer is grown on the *n*-type wafer from a solution containing silicon and a *p*-dopant. These layers are subsequently heated to permit interdiffusion of the atoms.

Although all of the preceding processes can produce a *p–n* homojunction, the properties required from the junction and the fabrication costs determine the fabrication method. Methods of making other kinds of junctions are similar to those used to make homojunctions, but the materials on either side of such junctions are dissimilar.

Action at the *p–n* Junction. When two pieces of silicon, one *n*-type and the other *p*-type, are brought into contact with one another, initially there are only electron carriers on the *n*-side of the newly formed junction and hole carriers on the *p*-side. This condition causes a large difference in electrostatic charge density across the junction. Immediately after contact, electrons and holes diffuse across the junction in opposite directions. Figure 2**a** illustrates the distribution of charges in a *n–p* junction solar cell. In the region away from the junction, donor and acceptor ions are neutralized by the presence of free charge carriers. Donor ions are dopant atoms that have contributed electrons to the crystal lattice and thus have positive net charges. Acceptor ions are dopant atoms that have contributed holes to the crystal lattice and consequently have net negative charges. The zone immediately adjacent to the junction is depleted of free charge carriers, which are needed to electrostatically neutralize the ions, and is called the depletion region. The width of the depletion region varies with the concentration of the dopants, but generally is less than 10^{-4} cm. In the depletion region, the unneutralized donor and acceptor atoms produce an electric field. This field causes an electrostatic or barrier potential, V_b, across the junction. V_b is a measure of the potential, which maintains the position of the majority carriers on their respective sides of the junction. Figure 2**b–d** shows simplified energy band diagrams of the same cell. The uppermost curved line in these drawings denotes the conduction energy level, E_c, for the electrons in a solar cell; the lowest curved line denotes the valence energy level, E_v, for the electrons. The cell's band gap energy, E_g, is represented as the distance between the E_c and E_v lines. The dotted line indicates the Fermi energy level, E_f, ie, the level of energy at which the probability of occupancy of an electron state is 50%; below this level, more than 50% of the available electron states are occupied. The relative horizontal position of the Fermi levels across the junction indicates the presence or absence of induced voltage.
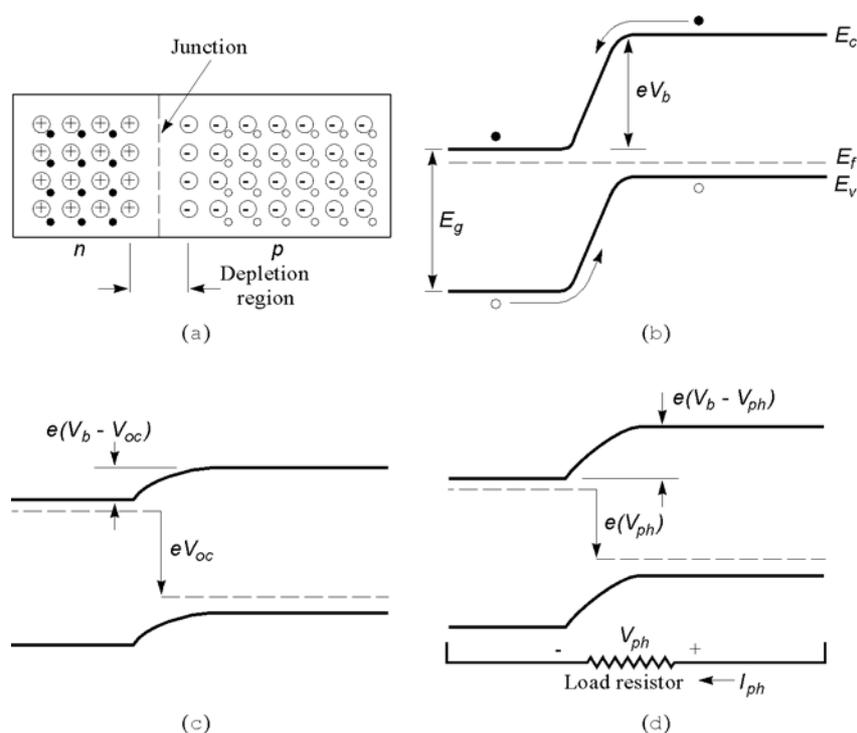
Fig. 2. (**a**) A schematic diagram of a $n–p$ junction, including the charge distribution around the junction, where ⊕ represents the donor ion; ⊖, acceptor ion; •, electron; °, hole. (**b**) A simplified electron energy band diagram for a $n–p$ junction cell in the dark and in thermal equilibrium under short-circuit conditions, where E_f represents the Fermi energy level. (**c**) For the same cell in sunlight and under open-circuit conditions where V_{oc} is open-circuit voltage. (**d**) For the same cell in sunlight and under load conditions where V_{ph} is photogenerated voltage and I_{ph} is photogenerated current.

In the normal operating temperature ranges for solar cells, almost all the extra valence electrons associated with the donor dopant atoms in the n-region escape their weak bonds and reach the conduction band, thereby becoming free carriers. In the p-region, the holes associated with the acceptor dopant atoms also are free but are in the valence band. The free electrons and holes are the majority carriers in the n- and p-regions, respectively. The number of majority carriers generally is determined by dopant concentrations and is not sensitive to either thermal or light excitation. However, the number of minority carriers, ie, holes in the n-region and electrons in the p-region, is sensitive to both thermal and light excitation. This sensitivity affects the operation of the solar cell.

In the dark, all the minority carriers in the n- and p-regions of a cell are generated by thermal excitation. Once the minority carriers in the p-region (free electrons) diffuse through the p-region to the depletion zone, they are swept by the built-in barrier potential, V_b, across the junction and into the n-region. In a similar manner, minority carriers in the n-region (holes) are swept into the p-region. The energy band diagrams in Figure 2 are for electrons; for holes, the diagrams should be inverted so that holes fall downhill as they are swept from the n-region into the p-region. This flow of thermally generated minority carriers in a solar cell in darkness is called a dark-drift current. The current is balanced by an opposing flow of charge carriers across the junction, ie, a back-diffusion of majority carriers, which are electrons crossing from n-region to p-region and holes crossing from p-region to n-region, flowing against the electrostatic potential V_b. Because majority carriers far outnumber minority carriers, V_b adjusts itself so that these two opposing currents are equal in magnitude, and equilibrium is established between the n- and p-region with the Fermi levels lining up on both sides of the junction. In the dark there is no output voltage and no net current.

When sunlight falls on a $p–n$ junction solar cell while it is short-circuited, the magnitude of V_b remains essentially the same as it was in darkness. Because the diffusion of majority current only varies with V_b, the majority current does not change. However, additional minority carriers are formed by photons, which are absorbed in both the n-region and p-region, and are swept across the junction. The flow of these minority carriers is in the same direction as the dark-drift current and is a net current flow, ie, the photogenerated short-circuit current, I_{sc}.

The same cell in sunlight, but under an open-circuit condition, cannot develop a net current flow. Instead, the cell achieves an equal internal flow of majority and minority carriers across the junction by reduction of its electrostatic potential from its original value V_b, thus there is no net current. This reduction allows a much larger diffusion current, which balances the photogenerated minority current I_{sc} (Fig. 2**c**). The decrease in barrier potential from V_b to $V_b - V_{oc}$ causes an open-circuit voltage, V_{oc}, of the same magnitude across the open-circuit terminals of the cell. Fermi levels are offset by V_{oc} or the net-induced voltage. Therefore, V_{oc} is equivalent to the reduction from the built-in barrier potential V_b, ie, the larger I_{sc}, the greater the barrier potential reduction. Although theoretically the maximum value of V_{oc} is V_b, this condition is possible only in a very high concentration of sunlight, ie, with extremely large I_{sc}. Furthermore, because V_{oc} has a value equal to or less than the barrier potential, cells with a large V_b usually produce a large V_{oc}, which is why cells with larger band gaps have large values of V_{oc}.

Under both short-circuit and open-circuit conditions, a solar cell produces no electric power, the power is consumed internally in the cell and

is dissipated as heat. When a resistive load is connected to a cell in sunlight, a photogenerated voltage, V_{ph}, is induced across the load and a current I_{ph} flows through it. The existence of I_{ph} requires that the flow of majority carriers be reduced from that in the open-circuit condition; there must be a higher barrier potential than in the open-circuit case (Fig. 2**d**). This higher barrier potential ($Vb - V_{ph}$) indicates a smaller reduction from V_b. Since the photogenerated voltage that is induced across the cell is the same as the photogenerated voltage V_{ph}, the magnitude of V_{ph} is always less than V_{oc}. The Fermi levels are offset by V_{ph}.

The photogenerated current I_{ph} is in the same direction as I_{sc}, but is always less than I_{sc} because the barrier potential under load conditions is always less than V_b, which results in a larger flow of majority carriers than that in a short-circuited cell. Thus, when a solar cell is under load, the current and voltage are always less than I_{sc} and V_{oc}, respectively; this condition is the curve-factor loss. Depending on the characteristics of the particular p–n junction and on the cell operating conditions, there is an optimal load resistance that maximizes the power output of the cell, ie, the product of its current and voltage.

When the temperature of a solar cell rises, cell conversion efficiency decreases because the additional thermal energy increases the thermally generated minority (dark-drift) current. This increase in dark-drift current is balanced in the cell by lowering the built-in barrier potential, V_b, to boost the majority diffusion current. The drop in V_b causes a decrease in V_{oc} and V_{ph}. Therefore, a cell's output, ie, the product of V_{ph} and I_{ph} decreases with increasing cell temperature. I_{ph} is less sensitive to temperature changes than V_{ph} and actually increases with temperature.

Efficiency

The most efficient silicon cells produced are based on p–n homojunctions and convert 23.1% of the energy in incident light set to simulate the global air mass (AM) 1.5 spectrum, an artificial reference spectrum used to standardize measurement of PV power, with an intensity of 1000 W/m² at 25°C (3). This is the definition of peak sunlight test conditions. In theory, silicon p–n junction solar cells can convert a maximum approaching 26% of the energy in AM 1.5 sunlight to electricity (4,5). Approximately 75% of the energy in sunlight is lost to factors intrinsic to the silicon material.

The largest single loss is caused by overly energetic sunlight; as much as 32% of the energy in sunlight is lost because sunlight contains many photons with energies larger than E_g for silicon, ie, >1.1 eV. Generally, only one electron–hole pair can be created by a photon regardless if its energy is more than 1.1 eV. The energy greater than E_g is lost in the conversion process and only produces heat within the cell. Another 24% of sunlight is useless for the conversion process in silicon because the photons have energies less than E_g and therefore are unable to create electron–hole pairs.

The maximum power is always less than the product of I_{sc} and V_{oc}. Other losses are caused by effects such as reflection, additional electrical losses, and shading by contact bars and fingers.

In comparison, p–n homojunction cells made of more costly semiconductor materials, eg, indium phosphide, InP, and gallium arsenide, GaAs, which have energy gaps of 1.2–1.4 eV, and maximum theoretical conversion efficiencies of ca 28–30% (6,7), depending on the device construction and layering of junctions. Materials with even higher band gap energies, eg, copper gallium diselenide, CuGaSe₂ ($E_g = 1.7$), have higher photovoltages but much lower photocurrents, which produce lower power-conversion efficiency in sunlight. The reduction in photocurrent occurs because there are fewer numbers of solar photons energetic enough to create electron–hole pairs in such materials.

Splitting the Solar Spectrum. Solar cells can be tailored to be optimally efficient in certain limited energy ranges. Because a single solar cell with one junction can convert only a fraction of the incident sunlight into useful energy, dividing the solar spectrum into energy ranges and making each range incident upon appropriately designed cells can result in increased conversion efficiency (8). In one approach, solar cells with different energy gaps are stacked in tandem so that the cell facing the sun has the largest energy gap. The top cell absorbs all the photons at and above its energy gap and transmits less energetic photons to the cells below. The next cell in the stack absorbs all the photons with energies equal to or greater than its energy gap, and transmits the rest downward in the stack, etc. In principle, any number of cells can be used in tandem. The maximum achievable efficiency of a three-cell stack is ca 35–40% at AM 1.5 with a thousandfold concentration of sunlight (9,10).

Designing tandem cells is complex. For example, each cell must transmit efficiently the insufficiently energetic photons so that the contacts on the backs of the upper cells are transparent to these photons and therefore cannot be made of the usual bulk metal layers. Unless the cells in a stack can be fabricated monolithically, ie, together on the same substrate, different external load circuits must be provided for each cell. The thicknesses and band gaps of individual cells in the stack must be adjusted so that the photocurrents in all cells are equal. Such an optimal adjustment is especially difficult because the power in different parts of the solar spectrum varies under ambient conditions. Despite these difficulties, there is potential for improvement in cell conversion efficiency from tandem cells.

Commercial Silicon Solar Cells

Silicon cells are hundreds of micrometers (μm) thick in order to facilitate handling with minimal breakage, although most solar radiation is absorbed in the first 20–30 μm. Light penetration decreases exponentially, proportional to $e^{-\alpha\tau}$, where α is the absorption coefficient of a material and τ is its thickness. The values of α for a given material vary with the wavelength of incident radiation; in silicon, α is 10^3–10^5/cm over most of the range of usable solar radiation.

The junction in a silicon cell usually is ca 0.2–0.5 μm from the surface of the cell. This shallowness minimizes the creation of photogenerated carriers in the layer above the junction. Such charge carriers might reach the crystal surface and recombine before being swept through the junction or recombine as a result of the high doping level, which would greatly decrease the photocurrent and therefore the cell efficiency. The crystal surface has many broken bonds that act as recombination centers. The top layer is thin and most of the charge carrier generation occurs below the junction. However, thinning the top layer increases its sheet resistance which is approximately inversely proportional to layer thickness. If the charge carriers that are swept from the lower layer into the top layer must pass through a large resistance before they are collected, much of the energy is dissipated. In conventional silicon cells, a comb or narrow metal grid lattice is connected to a current-carrying bus to collect charge carriers from the side of the cell facing the sun (Fig. 3). The fingers are small enough in total area so that minimal cell area is in their shadow.
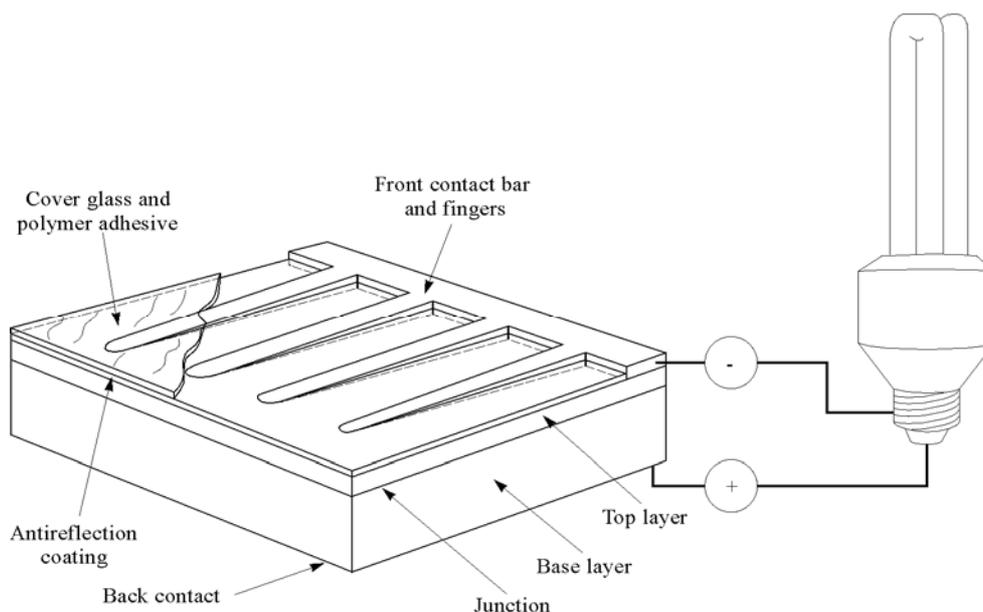
Fig. 3. Basic design of a commercial silicon solar cell.

Antireflection coatings are used over the silicon surface which, without the coating, reflects ca 35% of incident sunlight. A typical coating consists of a single layer of a transparent dielectric material with a refractive index of ca 2, which is between the index of silicon and air or cover material. Materials such as titanium dioxide, TiO_2, tantalum pentoxide, Ta_2O_5, or silicon nitride, Si_3N_4, ca 0.08-μm thick are common. The coating and a physically textured cell surface, such as small shaped facets, can reduce reflectivity to ≤5% (11). Solar cells are often encapsulated with a transparent adhesive to minimize potential degradation resulting from exposure to corrosive environments. The adhesive also bonds them to a protective cover glass, if one is used. The most widely used encapsulation materials are formulations based on silicone rubber or ethylene–vinyl acetate (EVA), which have proven to be of high durability over periods exceeding 15 years.

MANUFACTURING TECHNOLOGY

In the early 1970s, the first companies to apply low cost, mass production techniques to photovoltaics, a technology that had previously been considered an exotic aerospace technology, emerged. These techniques included the use of electroplated and screen printed metal paste electrical conductors, reflow soldered ribbon interconnects, and by 1977, low cost, automobile windshield-style, laminated module construction. Such processes benefitted from a substantial existing industrial infrastructure, and have become virtually ubiquitous in the present PV industry.

Opportunities for Cost Reduction.   Solar cells can be made from several different semiconductor materials, and these materials are available in a variety of physical states: single-crystal, polycrystalline (many small crystals), or amorphous (noncrystalline, eg, glass). Cells are assembled into packaged modules consisting of cells, interconnects, power leads, and a transparent cover or optical concentrator, depending on the type of module. Modules fall into two broad categories: flat-plate modules, used under ordinary sunlight, and concentrating modules, which include lenses to focus sunlight onto the solar cells for locations with generally clear sky conditions.

There is more than one way to make PV systems cost effective, ie, by making more efficient and less expensive devices, by stimulating the market toward higher sales in order to justify production volume increases to achieve economies of scale, and by combinations of these options. In any case, modules must operate reliably for long periods of time.

The cost of a PV device is determined by several factors. These include the kind of materials used and the amount of materials required, choice of substrates, device design, and fabrication processes. Crystalline devices are generally more efficient, but thin-film devices are anticipated to cost less in flat-plate configurations. The use of concentrated light permits retention of efficiency with simultaneous reduction in cost.

TYPES OF SOLAR CELLS

There are three basic technology options for making solar cells with dozens of variations on each. These approaches are conveniently grouped as follows: thick (∼300 μm) crystalline materials, concentrator cells, and thin (∼1 μm) semiconductor films.

Thick Crystalline Materials.

Silicon.   Crystalline silicon technology is the worldwide industry standard. The basic R&D was performed in the 1950s by Bell Laboratories and first commercialized in the 1960s for space power applications. Single-crystal silicon technology cost is challenged by manufacturers of cast block polycrystalline silicon, which is also in the thick category. The casting technique is less capital intensive than single-crystal growth but results in lower efficiency. The world's largest PV manufacturing plants use these crystalline silicon technologies and the fully burdened production cost differential is small. A doubling in sales volume and plant capacity along with investment in automation, wire saws for wafer cutting, and modern material handling methods might reduce cost about 40%, but at that point fundamental raw material costs and packaging (qv) requirements limit further cost reduction. This puts emphasis on greater utilization efficiency with the same essential starting materials and encourages efforts to develop alternative approaches. The options of ribbon silicon technology or concentrator cell approaches, which use thick cells based on silicon or gallium arsenide, are approaches toward circumventing the raw material cost problems.

The total cost of solar cells made from ingots reflects the costs of the silicon raw material used in forming an ingot, cutting and etching thin silicon wafers from the ingot, fabricating and encapsulating the cells, and assembling them into modules. An attractive cost-reducing approach is to grow good quality crystalline sheets directly from molten silicon. Smoothly grown sheets ca 100-μm thick require little or no cutting and polishing and incur little waste. Cells of relatively high efficiency have been fabricated from silicon sheets that are produced by growth-from-melt processes, eg, edge-defined, film-fed growth (EFG), and web-dendritic growth. The EFG technique consists of pulling a ribbon of molten silicon through a slotted die. The ribbon, which generally is polycrystalline with large crystallites, is shaped by the orifice in the die which is made from a material, eg, graphite, that is wetted by molten silicon. In the web-dendritic growth technique, silicon sheet, which generally is single crystalline with a twin plane passing through the center, is grown from the melt in a sheet between two silicon fibers.

Unfortunately, silicon sheets that are made from a melt often develop a granular or semicrystalline texture. The boundaries of the individual crystallite grains have many detrimental effects on photovoltaic conversion, ie, crystalline grain boundaries provide recombination centers for holes and electrons; boundaries behave as barriers to the movement of charge carriers, eg, horizontal grain boundaries isolate some charge carriers from the cell junction, and charge carriers that cross the junction must pass through resistive grain boundaries before reaching a contact sheet or finger; charge carriers can leak across the junction along grain boundaries; and undesirable impurities often diffuse much more rapidly along the grain boundaries than in single crystals, sometimes resulting in short-circuiting of the junction. Such difficulties have slowed the commercialization of these technologies. However, hydrogen passivation of grain boundaries has been effective in minimizing these effects and numerous groups are working to scale-up sheet and ribbon technologies to mass production (MW_{peak}/yr) levels. Figure 4 displays a schematic for these basic alternatives.
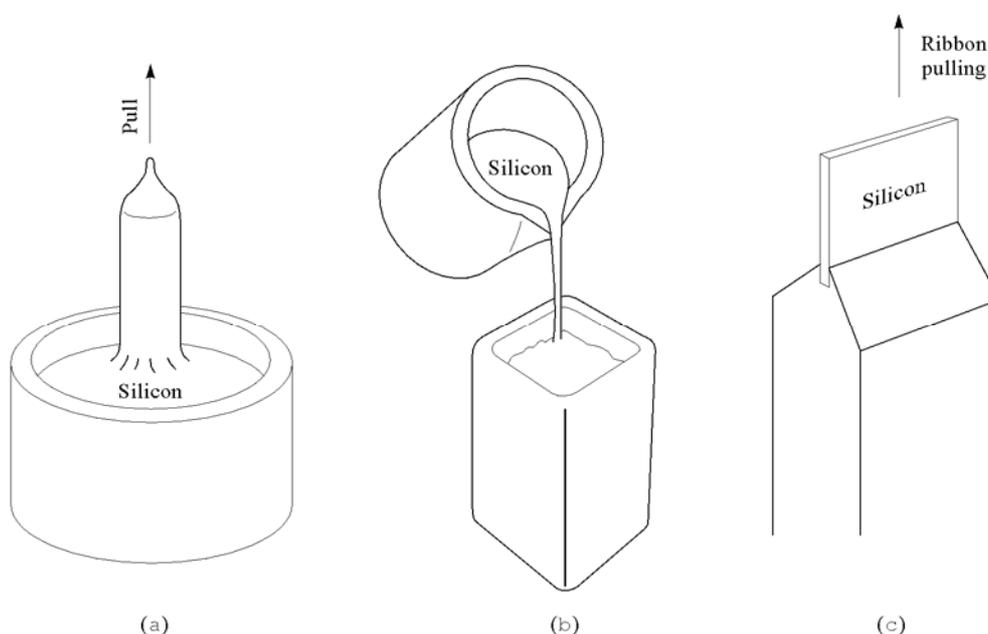

Fig. 4. (**a**) Single-crystal growth (Czochralski method), (**b**) casting, and (**c**) ribbon formation options for silicon.

Crystalline silicon technology is the most mature and best understood of PV technologies. Researchers have identified the principal barriers that limit efficiency and, as a result, since the mid-1980s laboratory cells have climbed from 18 to ~23% and commercial production from 12 to ~15%. This is a particularly impressive achievement since crystalline silicon was regarded as mature in the early 1980s.

A concept gaining support is a hybrid approach to making thick crystalline silicon efficient in thin layers. Although conventional crystalline silicon cells have gone from 400–600-μm thick to 200–300-μm, thin-film crystalline silicon cells have reached 10% efficiency while being only 10-μm thick.

Gallium Arsenide. Gallium arsenide is a promising material for gaining the advantages of high efficiency. It is superior to silicon in several respects. The E_g of GaAs, ca 1.4 eV, is higher than that of silicon and is in the range that provides the highest calculated conversion efficiency for a single-junction cell. Because of this high efficiency and the fact that it does not decline as rapidly as that of silicon cells with increasing temperature, GaAs single-crystal cells are attractive for use as concentrator cells.

Gallium arsenide solar cells advanced in the 1980s for space use because they weighed much less than silicon cells of similar output, since GaAs absorbs sunlight much more strongly than silicon. Thinner layers, ca 1–2 μm thick, can be used (12). Although the lower band gap of silicon allows more photocurrent than GaAs, the higher V_{oc} for GaAs cells more than compensates for the decreased photocurrent and results in higher conversion efficiency.

Two different high efficiency types of GaAs cell structures are being developed. These are GaAs homojunctions with a top window layer of $Ga_{1-x}Al_x$ and GaAs shallow homojunctions. Each type is being developed in order to minimize the effects of the recombination of charge carriers at the site of broken bonds in the top surface. Such recombination effects, which are more severe in GaAs than in silicon because of the shallower absorption depth of sunlight in GaAs, can severely reduce the photocurrent and therefore the conversion efficiency. Reported efficiencies of GaAs cells are ca 27.5% at AM 1.5 with a sunlight concentration of 205 and cell temperatures of 25°C (3). Silicon cells have achieved conversion

efficiencies of 26.5% at AM 1.5 with a 140-fold concentration of sunlight and cell temperatures of ca 25°C. Sophisticated multijunction solar cells such as GaAs–GaSb and GaInP–GaAs, with expected practical limits of about 40%, have exceeded 30% efficiency in laboratory configurations (13).

Concentrator Cells and Systems. Concentrators circumvent the problem of high semiconductor material cost by using mirrors or lenses to concentrate sunlight on small surface areas of more expensive solar cells. Concentration allows more power to be produced from a given amount of photosensitive material. This can solve the cost problem but may create new challenges. First, concentrators only operate efficiently in areas with clear sky conditions (output is ~0 on hazy days, unlike flat-plate modules), and large scale (>500 W_{peak}) is generally necessary to permit the cost-effective installation of tracking structures. Within certain limits, the concentration strategy can result in cost reduction. The photocurrent generated in a solar cell increases linearly with increasing light intensity within practical limits of concentration, and photovoltage increases roughly as the logarithm of the increase in intensity up to the built-in barrier voltage. The result of these combined effects can be to increase the conversion efficiency as well as boost net electrical output. However, the cells must be specially designed to minimize resistive losses because of the increased photocurrent densities. In addition, the concentration of sunlight often causes increased cell temperatures, so much so that conversion efficiency suffers rather than benefits from the concentration; therefore, some concentrator cells are equipped with cooling systems. Although it may be possible to utilize both the electricity and the heat produced in concentrator cell systems, the technology involved in such utilization has not been well developed.

Concentrator optics vary from low ratio designs, eg, concentration of sunlight of an order of magnitude by Winston collectors, which do not require elaborate tracking of the sun, to much higher ratio systems based on parabolic mirrors or Fresnel lenses and which require precise, two-axis tracking (14). Three types of concentrator systems are being developed which operate at low level (<30 times), mid-level (100–400 times), and high level (>400 times) sunlight concentrations. The cell specifications and engineering requirements for each of these types of systems are quite different. Specially designed silicon has shown potential for use in concentrator systems.

Thin Film. In the thin-film approach, raw material usage is generally more than two orders of magnitude less and patterning is more direct. In some thin-film approaches, certain individual layers may be only 50 atoms thick, which means that large-area uniformity of coating is the key to success. These coatings must be both optically and electrically uniform over areas the size of about a square meter. The technical decisions are complex and may be ordered as follows: (*1*) What substrate is to be coated? The principal choices are glass, steel, ceramic, or plastic. (*2*) What materials are to be deposited? The principal semiconductor options are amorphous and polysilicon, cadmium telluride, copper indium diselenide, and alloys of these basic options. The most significant conductor options are silver, nickel, aluminum, tin oxide, zinc oxide, indium oxide, and some alloys of these choices. (*3*) What deposition process is to be utilized? The options are vacuum evaporation, sputtering, glow discharge, chemical vapor deposition (CVD), electroplating, spraying, and screen printing. (*4*) How are the layers to be patterned? These options include screen printing, laser scribing, mechanical scribing, and photolithographically defined wet etching.

Good solar cell results have been obtained from cells of materials, including polycrystalline silicon, amorphous silicon–hydrogen (α-Si:H) alloys, Cu_xS–CdS, $CuInSe_2$–CdS, and CdTe.

Polycrystalline Silicon. Thin-film polycrystalline silicon cells should be at least 10–30-μm thick for efficient absorption, depending on the effectiveness of the light trapping techniques (15). Such thickness requires photogenerated charge carriers to diffuse similar distances to reach the junction. Minimization of recombination and loss of these carriers can be effected by use of efficient polycrystalline layers, which have as few horizontal grain boundaries as possible within the absorption zone; the preferable condition is that of crystallite grain boundaries that are vertical or normal to the substrate or the junction. The lateral extent of a crystallite should generally be at least three or four times greater than the absorption distance, so that the vertical grain boundaries do not significantly reduce the photocurrent as a result of recombination. The most efficient thin-film polycrystalline silicon cells produced are ca 15% efficient at AM 1.5, which is lower than the best efficiency for single-crystal silicon but of significance to opening options for cost reduction. These polycrystalline, thin-film silicon cells are formed by CVD of silicon or crystallization from supersaturated silicon solutions onto ceramic or glass.

Amorphous Silicon. Amorphous alloys made of thin films of hydrogenated silicon (α-Si:H) are an alternative to crystalline silicon devices. Amorphous silicon alloy devices have demonstrated small-area laboratory device efficiencies above 13%, but α-Si:H materials exhibit an inherent dynamic effect called the Staebler-Wronski effect in which electron–hole recombination, via photogeneration or junction currents, creates electrically active defects that reduce the light-to-electricity efficiency of α-Si:H devices. Quasi-steady-state efficiencies are typically reached outdoors after a few weeks of exposure as photoinduced defect generation is balanced by thermally activated defect annihilation. Commercial single-junction devices have initial efficiencies of ca 7.5%, photoinduced losses of ca 20 rel %, and stabilized efficiencies of ca 6%. These stabilized efficiencies are approximately half those of commercial crystalline silicon PV modules. In the future, initial module efficiencies up to 12.5% and photoinduced losses of ca 10 rel % are projected, suggesting stabilized module aperture-area efficiencies above 11%.

As with all thin-film PV technologies, the projected manufacturing costs of α-Si:H alloy PV modules fall rapidly with annual manufacturing volume, ie, MW_{peak}/yr. The primary driver of this volume cost reduction is the volume–cost relationship of commercially available thin-film processing equipment. Thin-film coating machines often have capacities equivalent to 3–5 MW_{peak}/yr, so that manufacturing economies of scale are more fully realized at the 10–15 MW_{peak}/yr range. Lower manufacturing output rates generally suffer from high capital equipment costs, due to the large capacity excess to be depreciated, or from high labor costs, due to reliance on manual processing in lieu of expensive large capital equipment.

Amorphous silicon technology has advanced considerably from the first generation of single-junction α-Si:H products introduced in the 1980s. Throughout the 1980s, single-junction α-Si:H modules were at best 5.5% efficient, and often less than 4% efficient in actual field use. Single-junction α-Si:H technology and α-Si:H manufacturing techniques and equipment were successful in yielding low module fabrication costs ($/m²), but low module efficiencies resulted in high cost per unit power ($/$W_{peak}$) generally well above that of crystalline silicon. Also, the first generations of thin-film module encapsulation techniques in many cases did not adequately protect the active layers and severe (15–35 rel %) losses in power occurred with prolonged outdoor exposure. Overall, the first generation of single-junction amorphous silicon failed to achieve high power, low cost PV power modules with consistent high manufacturing production yields. As a result of these experiences, improvements were made in materials processing, optical design, cell interconnection, and module encapsulation, which significantly improved single-junction α-Si:H module performance and are valuable in the design of newer thin-film module products.

The key determinants of future cost competitiveness of α-Si:H PV technology are α-Si:H deposition rates, module production yields, stabilized module efficiencies, production volume, and module design. Reported α-Si:H deposition rates vary by more than a factor of 10, but most researchers report that the high quality films necessary for high stabilized efficiencies require low deposition rates often due to high hydrogen

dilution of the Si (and Ge) source gases (see SEMICONDUCTORS, AMORPHOUS).

Copper Sulfide–Cadmium Sulfide. This thin-film solar cell was used in early aerospace experiments dating back to 1955. The Cu_xS band gap is ca 1.2 eV. Various methods of fabricating thin-film solar cells from Cu_xS/CdS materials exist. The most common method is based on a simple process of serially overcoating a metal substrate, eg, copper (16). The substrate first is coated with zinc which serves as an ohmic contact between the copper and a 30-μm thick, vapor-deposited layer of polycrystalline CdS. A layer is then formed on the CdS base by dipping the unit into hot cuprous chloride, followed by heat-treating it in air. A heterojunction then exists between the CdS and Cu_xS layers.

Most of the sunlight is absorbed by the Cu_xS layer, therefore the CdS layer does not have to be very thick because it does not absorb much sunlight. However, because of the fabrication process, the CdS layer must be thick enough to prevent Cu_xS from diffusing along the grain boundaries deeply enough to reach the metal substrate, thereby short-circuiting the heterojunction.

Laboratory thin-film cells that are fabricated using this cell structure demonstrate a conversion efficiency of slightly greater than 10% (12). Unfortunately, efforts to create a device that is stable for long periods have been unsuccessful and little effort to develop this material is underway.

Cadmium Telluride. Cadmium telluride [1306-25-8], CdTe, is another promising thin film. CdTe is a well-known semiconductor often used in high performance infrared sensors. CdTe absorbs visible light very strongly, and very thin films (1–2 μm) are sufficient to absorb most sunlight. Small-area thin-film CdTe solar cells have been fabricated with sunlight-to-electricity conversion efficiencies near 16%, comparable to crystalline silicon solar cells in large-scale manufacturing. Large-area monolithic integrated CdTe modules have been fabricated with efficiencies of ca 10%, comparable to crystalline silicon modules commercially available.

CdTe technology is particularly attractive because of its potential for low cost manufacturing techniques, including electrodeposition, spraying, and screen-printing–nonvacuum methods that are less capital-intensive than most other thin-film processes. Given the low manufacturing costs possible with thin-film processing techniques and the high efficiencies of CdTe photojunctions, it is widely anticipated that in full-scale production CdTe PV modules will be competitive in performance, price, and durability.

Companies in the United States, Japan, and Europe are actively working to commercialize CdTe PV technology. CdTe PV modules are available in limited quantities and sizes from one Japanese manufacturer, and two U.S. companies (Golden Photon in Colorado and Solar Cells Inc. in Ohio) have announced their intention to market CdTe PV products in the near future.

Copper Indium Diselenide. $CuInSe_2$ (CIS) has proven to be one of the most promising thin-film photovoltaic materials. CIS alloy materials have yielded small-area (ca 1 cm²) laboratory devices with efficiencies in excess of 17% and large-area (ca 0.5 m²) monolithic integrated modules with efficiencies in excess of 11%, and have shown excellent radiation hardness.

$CuInSe_2$ is an ideal thin-film photovoltaic absorber material. The CIS band gap is near the optimum for photovoltaics, ie, low enough to absorb much of the useful solar spectrum and high enough to generate high operating photovoltages at normal outdoor operating conditions. CIS and its alloys exhibit strong optical absorption; films of $\leq$1-μm thickness are sufficient to absorb most sunlight. The grain boundaries and surfaces of CIS and its alloys are electronically benign, so that simple polycrystalline films yield high efficiency photovoltaic devices without complex grain boundary passivation processing. The defect chemistry of CIS materials is such that its microstructural and compositional tolerance are high, thus compositional variations, eg, Cu–In atomic ratio, of ±5 atom % can be tolerated. This tolerance of microstructural and compositional variations relaxes the requirements for processing precision and uniformity without significantly impacting the overall device efficiency. High efficiency CIS junctions can be fabricated with relative ease. CIS forms stable, high conductance ohmic contacts with molybdenum metal, and high quality p–n junctions can be formed with thin CdS layers and standard transparent conductors like zinc oxide and indium–tin oxide. CIS PV junctions are stable. CIS devices can be made with simple monolithic interconnects between individual cells, allowing the fabrication of large monolithic integrated modules that minimize manufacturing labor requirements. CIS modules can be packaged simply using the pottant–glass encapsulation techniques proven for crystalline silicon PV products. Packaged CIS modules have proven durable in long-term outdoor tests (see PACKAGING, ELECTRONIC MATERIALS).

The technology forefront for CIS photovoltaics is twofold: graded alloys and large areas. CIS PV technology is evolving toward graded CIS alloy materials containing sulfur and gallium. CIS alloy absorbers can yield significantly higher photovoltages at slightly lower photocurrents, thus providing higher overall device efficiencies. Sophisticated composition grading allows the introduction of back surface fields and front surface minority carrier recombination control to yield higher efficiencies. These graded alloy materials can be formed by the co-evaporation techniques in use for laboratory experimentation, but are difficult to replicate on large areas using industrial physical vapor deposition processes that might be used in manufacturing.

CIS PV technology is evolving toward larger areas as the technology progresses from research laboratories to production factories. Processing on large-area substrates and production of large-area modules are essential in achieving low manufacturing costs. The point–source co-evaporation laboratory techniques used to develop the graded CIS alloys necessary to achieve the highest efficiencies are difficult to control on large areas. Physical vapor deposition (PVD) techniques have been developed to deposit basic CIS materials on large areas, but these PVD techniques are not well suited to the deposition of graded alloy materials. The PVD techniques generally require multistep processing and high substrate temperatures. Multiple steps complicate the fabrication sequence and add cost. The high substrate temperatures required for optimal PVD materials quality limit the options for usable substrates.

Thus, CIS is a promising photovoltaic material, but improved processing techniques are needed to achieve commercial production of advanced high efficiency CIS alloy materials. Table 1 summarizes the laboratory and commercial status of significant PV technology.

Table 1. Photovoltaic Technology Overview

	Flat plate				Wafer concentrator	
	Thick film		Thin film			
	Self-supported	Substrate	Alloy	Compound	Single-jun	Multi-j

type	Cz silicon	Poly-Xtal Si	EFG	Web	MIS Si	Si film	Spheral Si	Amorphous	CIS	CdTe	ction Silicon	unction III–V
initial PV demon-stration	1954	1976	1974	1959	1981	1987	1983	1976	1975	1971	1954	1965
theoretical efficiency,[a] %,	~26	~22	~20	~24	~24	~20	~18	~20	~22	~25	~26	~40
state-of-art cell, %	23.1	17.7	~16	18.3	~16	~15	~12	13	16.4	15.8	25.6 at 140×	32.6 at 100×
state-of-art module, %	18.2	12.2	~11.5	~15	na	~11	~10	~10	~11	~10	20.3 at 80×	~18 at 100×
commercial module, %	12.5	11	10.5	na	10.5	10.5	na	5	na	na	17 at 30×	na
	BHEL	DASA		Ebara	Nukem	Astropwr			ISET	BP Solar	Entech	na
	BP Solar	Eurosolare	ASE Am-erica					Advanced PV Systems	EPV		SEA Corp.	
representative industrial participants	CEL	Kyocera					Texas Instruments	Fuji Elect.	Siemens	Golden Photon	Sun Power	
		Photowatt						Intersolar	SEO Solar	Matsushita		
	Heliodinamica	Shell/R&S						Kanekafuchi				
	Helios	Solarex						NAPS France	Lockheed Martin	NAPS Finland		
	Isofoton							Sanyo		Solar Cells		
	Sharp							Solarex				
	Siemens							Taiyo Yuden				
	Solec							USSC				
								ECD				

[a] Air mass = 1.5, 1000 W/m^2, at 25°C.

ELECTROCHEMICAL PHOTOVOLTAIC CELLS

The application of photoelectrochemistry in solar energy conversion technologies includes biomass conversion, photoelectrolysis, photogalvanic cells, electrochemical photovoltaic cells, etc (17–19). In electrochemical photovoltaic cells, electric energy is converted directly from sunlight by absorption of light in a semiconductor electrode. In many respects, these cells closely resemble conventional solid-state cells, except that the charge-separating barrier layer is formed at the interface between a semiconductor surface with a liquid electrolyte. When sunlight is incident on the semiconductor electrode, free holes and electrons are created. The relevant minority carriers must migrate to the interface and be separated; these carriers then react with the electrolyte either through oxidation or reduction. The counterelectrode reverses the reaction, thereby maintaining the electrolyte balance. The semiconductor electrode material may be either polycrystalline or amorphous material because in some cases the poorer material properties cause relatively little degradation of conversion efficiencies. In addition, incorporation of a third electrode may make possible *in situ* storage. The main disadvantage of these cells is the instability of the semiconductor electrode, especially under sunlight, for extended periods of operation. Electrochemical cells could be inexpensive, since the electrode–electrolyte barriers usually are easy to form, but appropriate deployment strategies have not yet been identified. In addition, the stability problems encountered to date (ca 1995) have been extensive.

BALANCE OF SYSTEMS

A solar photovoltaic system contains, in addition to solar cells and module(s), an array structure to support the modules, power-conditioning circuitry for control and modification of the output, and a means of storing energy if required. All elements beyond the module are referred to as balance-of-system (BOS) components. The cost of BOS items is nominally about equal to the cost of the PV module. However, the BOS fractional cost contribution can vary from one- to two-thirds of the total installed cost of a system, depending on application. The direct current (dc) produced by solar cells must be changed to alternating current (ac), when the power is to be connected to commonly found utility power loads (20,21). For many applications, electric storage, eg, in batteries, is needed to provide power when the cells are not illuminated, to supplement output of the cells during transient loading, or to aid in utility power system load leveling (22). In addition, a means of regulating the flow of power between the solar array, energy storage, and load is often required (23,24). The development of less expensive storage for the solar photovoltaic system, eg, flywheels, pumped water, and fuel cells (qv), has been described (25–29). The exact mode of storage depends on the particular application of the photovoltaic system. For example, if the photovoltaic system is used in a rural residence, a small automotive battery is often used. However, if the system is

associated with a utility grid, the storage is centralized to the main utility where pumped water may be the storage technique.

Material Availability and Environmental Impact

Photovoltaic systems must satisfy four principal requirements before solar photovoltaic conversion can provide a significant portion of general energy needs. The system costs must be low enough to be competitive with other means of energy generation, the amount of energy generated during the life cycle of a photovoltaic system must be substantially greater than the energy required to fabricate the system to meet the criteria of a sustainable technology, the materials used in the cells must be available to generate a substantial portion, ie, at least a few percent of world energy needs, and the fabrication and utilization of the conversion systems should not cause more environmental problems than other competing energy systems.

Silicon is the second most abundant element in the world and is not toxic. Inherent in the use of materials other than silicon for solar cells are challenges of material availability and environmental safety. In terms of production of CdS-based cells, sulfur is abundant, but the world's resources of cadmium, tellurium, selenium, and indium are much less than those of silicon (30). However, these resources are several orders of magnitude greater than the amount needed to provide photovoltaic power production of 50,000 MW/yr. Similarly, although arsenic is plentiful, the supply of gallium for GaAs cells is limited. However, studies have concluded that the gallium supply also is sufficient for substantial manufacturing scale (31).

Although photovoltaic conversion is nonpolluting, environmental, health, and safety aspects must be considered, especially with regard to harmful emission and waste products resulting from the production of the solar cell modules. These considerations apply to silicon cell production, since various processing steps, eg, doping, may involve toxic materials. For materials, eg, CdTe, GaAs, and $CuInSe_2$, the presence of toxic Cd or As in the material and device processing must be carefully examined. In addition, the large deployment of such cell modules in terrestrial applications occur only when the long-term safety to the environment is assured. It has been shown that, with proper encapsulation and a proactive recycling program, it should be possible to minimize environmental concerns.

Photovoltaic Markets

The character of the PV market has undergone a substantial shift since the 1970s. In 1975, PV systems were installed exclusively to power remote industrial loads such as telecommunications repeaters, offshore aids to navigation, and cathodic protection systems. In the early 1980s, the installation of several multimegawatt centralized utility PV power plants raised expectations of rapid penetration into the potentially large utility market. Sharp reductions in oil prices curtailed most of the PV utility activity, and the balance of the decade saw the development of the off-grid, rural consumer market segment that dominates the PV business.

In the mid-1990s, utility applications have once again begun receiving a great deal of attention due to a profound paradigm shift that appears to be taking place in the utility industry. Rather than replacing or adding large central fossil-fueled or nuclear generation facilities, small PV systems deployed at the outer extremities of the grid can be cost-effectively used to manage demand profiles, defer transmission hardware upgrades, and support electrical service quality (voltage, power factor, etc) during periods of peak demand in locations where the utility grid transmission is unidirectional (32,33).

PV Market Segment Categories. Solar modules are used to provide power to a broad range of industrial, commercial, and consumer systems and products. Most participants in the PV industry use the following categories to describe the various market segments, which group applications by functional product requirement, system type, sales channel, and client base. These include the following: specialties, eg, spacecraft circuits, calculator chips, automobile sunroofs, and building facades; industrial power, ie, telecommunications, warning/signal lights, and remote data gathering; rural and off-grid electrification, eg, lighting, water pumping and purification, refrigeration, and recreational travel and boating; consumer convenience, eg, garden and security lighting and small battery charging; and grid-connected power, ie, distributed grid support and peaking power augmentation.

As PV module selling price has decreased, new markets have progressively emerged. This combination of market growth and price decrease has provided a smooth evolutionary path for the commercial industry of the 1990s.

Specialties. The specialty items business segment is principally a collection of niche market opportunities, including aerospace, eg, satellite power systems, and consumer electronics, eg, calculators. The aerospace industry is not much larger in terms of industry-wide revenues in the 1990s than it was in the 1970s. There are a few small specialty firms that produce cells with exacting quality assurance procedures that do not permit significant deviation from the manufacturing processes in use since the 1960s.

Perhaps the most familiar example in the specialty items category is the consumer electronics market which consists primarily of solar-powered calculators and watches. Although volumes are large in terms of units sold, the revenues are relatively small. Further, the competition is fierce for any photovoltaics manufacturer who seeks to sell commodity solar cells to the consumer goods producer.

Industrial Power. The original use for terrestrial solar modules was in industrial applications. These systems employ an array of modules typically between a few hundred watts and a few kilowatts to charge storage batteries, which are then used to power the load. Usually the batteries contain enough reserve to deliver power for up to a week in the case of bad weather. Industrial systems are located in areas where no power grid exists, and where the alternative forms of remote power generation, such as diesel generator sets or thermoelectric generators, are either impractical or economically unfeasible. Desirable module attributes are high efficiency to reduce the size and therefore the cost of the site and mounting structure, and high reliability (34). In general, the cost of the solar array is a minor percentage of the entire project cost, thus the market size is relatively inelastic to module price.

Examples of remote industrial applications are microwave, radio, and cellular telephone repeaters; supervision, actuation, and data telemetry systems for highway warning signs, wellheads, oil and gas pipeline valves, reservoirs, dams, etc; aids to navigation on offshore buoys, lighthouses, oil and gas platforms, bridges, tanks, masts, and railroad crossings; and cathodic protection systems on pipelines (qv), tanks, and wellheads to inhibit corrosion.

Rural and Off-Grid Electrification. Rural consumer applications relate more to people as contrasted with electrical equipment, and in this sense the service provided by the solar system is no longer simply electrical power supply, but rather light, television, drinking water, etc. Because these services require a much broader spectrum of system hardware, eg, pumps, light bulbs and fixtures, or television sets, than industrial systems, and because the local conditions in the various end use regions are so varied, such systems have been most successfully marketed through in-country distributors. These distributors, or system integrators, buy modules from the PV module manufacturers, but design and source the

balance of the components by themselves to fit the local requirements. Local content is mandatory for practical as well as political reasons (35,36). The attention placed on ecological and job issues around the world makes it inevitable that government emphasis on local content, including local manufacturing, will increase. The small modular nature of photovoltaic products is a good match to this requirement.

The rural consumer customer base is large and remarkably diffuse. Unlike industrial systems, the price of the solar array comprises a large fraction of the total system price, and is thus highly leveraging to this market segment. The alternative to a PV system, in many cases, is doing without the service or accepting an inferior level of comfort, eg, contaminated water or kerosene lighting. Reducing the up-front transaction cost is important (37).

Examples of rural consumer applications include small ($\sim 50-1000$ W_{peak}) homelectric or solar home systems including a few fluorescent lights, a television set, and/or radio for remote homes and vacation cabins; larger ($\geq 10-20$ kW_{peak}) systems for a village power supply or to provide power to a field hospital, clinic, or school; water pumping systems for drinking water or livestock watering as well as for low head microirrigation systems; and battery charging systems mounted to the roof or deck of recreational vehicles and pleasure boats, providing power for lights and, perhaps, a television (38–40). The rural market segment is driving the majority of growth in the PV industry. The world bank has estimated that over 1.7 billion people live without any electric service and that the number is increasing. PV production is expanding to meet this demand. Such progress permits expansion of manufacturing capacity and the cost reduction which accompanies both increased production scale and normal learning curve efficiencies. If just one-half of the homes without any electricity were to have 50 W of PV power (10,000 MW), it is estimated that the volume of PV production would be enough to see module prices fall to a level near $1.00/W_{peak}$, which translates to an electricity price of approximately $0.10/kWh \pm 25\%$, depending on the cost of money and BOS requirements.

Consumer Convenience. The solar powered garden light, with its simplicity and design for functionality, was introduced through mass merchandise retail outlets in the mid-1980s. These units helped popularize PV and evolved into broad use for decorative lighting applications and as high performance security lighting systems. These small systems have served as the test for lighting products of all types.

Grid-Connected Power. This group of applications represents the long-term goal of PV technology, to generate large amounts of power in conjunction with the existing utility grid, thereby displacing fossil fuel use. Implementation concepts range from distributed systems, whereby each house is equipped with a solar array of several peak kilowatts, all feeding the grid in parallel, to large centralized stations similar to the multimegawatt stations constructed in California during the early 1980s (41).

Utilities have become familiar with PV in traditional industrial applications such as tower lighting, telemetry, valve and gate actuation, cathodic protection, communications systems, and security lighting. These systems generally include a fixed tilt crystalline silicon array, charge controller, and battery storage, and are individually designed and installed by a network of system integrators. Such applications are cost effective for module prices below $7-9/W_{peak}$, and the market is relatively inelastic to pricing (42).

Stand-Alone Microutility Projects. Utilities have also become familiar with PV in a separate group of associated applications which are small (~ 1 kW_{peak}) utility-owned stand-alone domestic power supply systems commonly referred to as "service without the wire." Typically, these systems are essentially identical to a remote industrial system, with the addition of an inverter used to power common appliances that require alternating current. Several utilities are investigating the possibility of installing, owning, and operating such systems as a cost-effective alternative to power line extension.

Microutility systems are categorized on the basis of stand-alone character, ie, primary energy supply, as opposed to line-tied or peaking power supply. These systems are installed in locations without any existing primary source of electricity, in some cases as a replacement or in conjunction with small (≤ 50 kW) diesel generator sets. Such PV microutilities are the most cost effective for electrifying isolated islands and villages in developing nations seeking to prevent mass migration of the rural population to overcrowded urban centers. A typical system configuration includes a tracking PV array that charges a storage battery, which in turn feeds a small a-c distribution grid through the use of a static (battery-tied) inverter.

Battery storage is used to furnish energy at night and during short periods of inclement weather. Rather than designing the battery capacity for an extended period of load autonomy, a small backup generator is included to recharge the battery when necessary. This design philosophy results in emphasizing the value of a relatively small battery which charges and discharges a significant portion of its total stored energy every day. The static inverters used in such systems are standard equipment in widespread use for uninterruptible power supplies (UPS). Some additional inverter output protection, eg, surge suppression, measures are generally included by the PV equipment suppliers.

Microutilities are often sited in areas without existing sources of electric power, and often in countries with limited ability to pay the large up-front capital costs inherent to PV systems. Large-scale usage of PV technology is constrained by the lack of sufficient financing needed to cover the high capital cost, which in many cases must be weighed against subjective and abstract societal and political values. As a further complication, rapid government turnover in many developing countries tends to lead to "quick fixes" with low capital costs, rather than solutions which might provide lower life cycle costs realized over a longer period (43).

The key to this microutility market segment, therefore, is financial in addition to technological. It is likely that any significant success in this market will result directly from the creation of a suitable financing strategy.

Grid Voltage Support. This application has been the focus of increasing discussion during the 1990s, precipitated by numerous utility studies detailing a system planning paradigm shift and concern for the consequences of deregulation in the United States. Specifically, the thinking is based on a detailed evaluation of various low capacity (ie, ≤ 1 MW) decentralized generation and distribution options, compared to the previous evaluations based entirely on 200+ MW centralized generation increments. This finely tuned evaluation quantifies some of the commonly accepted but previously subjective benefits of PV systems such as modularity, quick construction time, and inherent dispatchability, ie, a local match between PV system daily output profile and summer peaking utility demand contour. Similarly, the relatively high costs associated with regular (eg, noon–7 pm, July–Sept.) overload of end-of-the-grid feeder circuits become visible when analyzed in greater detail. This type of application was first demonstrated in 1982 with a 1 MW installation in the high desert of Southern California next to the Southern California Edison Lugo substation.

In the grid-connected market, energy prices and regulatory policies have a primary impact on the growth rate and form of market penetration. The market is geographically fragmented based on competing energy prices and options for electricity supply as well as the rates of localized demand growth and sunlight availability. In general, U.S. utilities anticipate that photovoltaic systems can compete into the twenty-first century for distributed voltage support generation additions, as PV power system selling prices reach the $3.00–$6.00/watt_{ac}$ total installed system price. In 1994 prices as

low as $6.25/W$_{ac}$ were quoted to the Sacramento Municipal Utility District for its pioneering PV program. The core of the government role in accelerating utilization of PV power is to provide support, especially with regulatory groups to permit early market entry.

The new utility planning model ascribes a significantly higher value to PV-generated electricity than has been previously considered in the context of large-scale utility applications. Furthermore, a study by Pacific Gas & Electric indicated that roughly 10% of the total 2000 feeder circuits could cost-effectively utilize PV systems of this type, ie, 500 kW$_{peak}$ (32). Therefore, the addressable market only within the PG&E network (constituting ~3% of total U.S. generating capacity) is on the order of 100 MW$_{peak}$. This market segment exhibits high price/demand elasticity, since the initial market penetration occurs on the highest cost, lowest volume segments of the grid.

Distributed Rooftop.   Distributed rooftop-mounted PV systems are usually thought of as an alternative to centrally sited PV power plants such as those previously discussed. Each system, based on a flat-plate integrated panel ranging from 1–3 kW$_{peak}$, is connected to the utility grid by means of an individual line-tied inverter. As with the grid support application, power from the aggregate arrays serves to decrease the peak summertime demand on the utility central generation capacity. The arguments for this approach can be divided into two groups, namely quantitative and qualitative (44).

Quantitative arguments for rooftop-mounted arrays deal primarily with the cost savings captured by avoiding the need for an array support structure, since the price of the roof has already been paid. Counter-arguments include the lack of economies of scale (as with central systems), costs associated with individual engineering, permitting, and installation of each system, and the fact that roof-mounted systems can be fixed; as opposed to tracking, resulting in a lower capacity factor per installed peak kilowatt. In some areas, such as Japan, population density and the high cost of farmland virtually preclude the use of centralized systems, and strongly favor the distributed rooftop-mounted approach.

Qualitative arguments deal primarily with the sense of ownership and security which result from individually owned generation systems. Additional complexity will arise from the aesthetic criteria specific to both individual homes and the surrounding community. Of course, the autonomy inherent in distributed rooftop arrays probably constitutes an institutional barrier to their acceptance by some utility companies, unless they are involved in the financing and/or marketing chain.

Demonstration Projects.   Demonstration projects, many government funded, have been important in the development of the solar industry. Throughout the latter part of the 1970s and the early 1980s, there was a concerted effort on the part of the U.S. government to stimulate the growth of the industry through large block purchases of modules. These modules were used for many different systems, most notably to power houses, ie, lighting, refrigerators, and water pumps on various Native American reservations. Substantial solar tax credits covering up to 50% of the initial system cost in some cases also provided a demand side stimulation of the market. Thousands of rural solar home systems were installed during this period. The result of this activity is a solid, long-term performance history of proven PV system performance which has been independently verified by a wide variety of customers. Some forms of accelerated depreciation and long-term power-purchase contracts are in place that deliver equivalent financial incentives, without creating a dependency on one-of-a-kind subsidies.

In Europe and Japan, government-funded demonstration projects are being actively pursued as a method of direct stimulation of the PV industry.

Market Size and Distribution.   The market for PV modules has grown at an average annual rate of more than 15% since the 1980s to approximately 68 MW$_{peak}$/yr (1994) (45). With increased involvement of utilities and lending institutions, such as the World Bank, this rate is expected to continue. Figure 5 provides an overview of the historical and projected market growth.
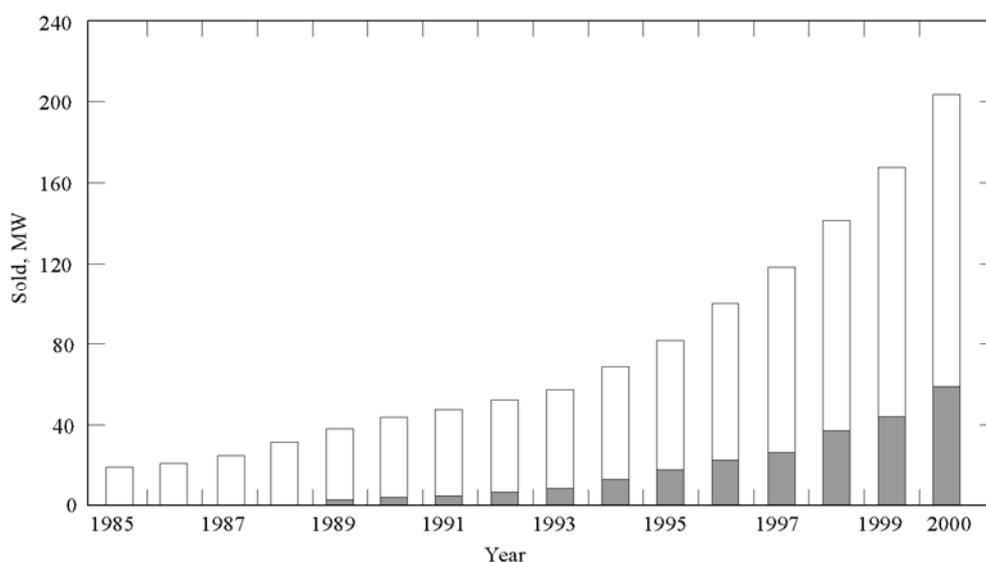

Fig. 5. Worldwide PV business from 1985 through 2000, where (□) represents developing countries and (■), developed countries.

A significant factor in the growth of the industry is an increased participation by local entities in all aspects of the technology from market development to manufacturing, as is represented in the differentiation shown in Figure 5 between products manufactured in developed countries and developing countries (46). This is a reflection of the strong differential growth rate in the rural consumer segment, which accounts for nearly half of the total PV market, versus slightly more than 25% at the start of the 1990s. The rural market segment and the industrial market are expected to remain a significant portion of the total business through the remainder of the twentieth century (Fig. 6).
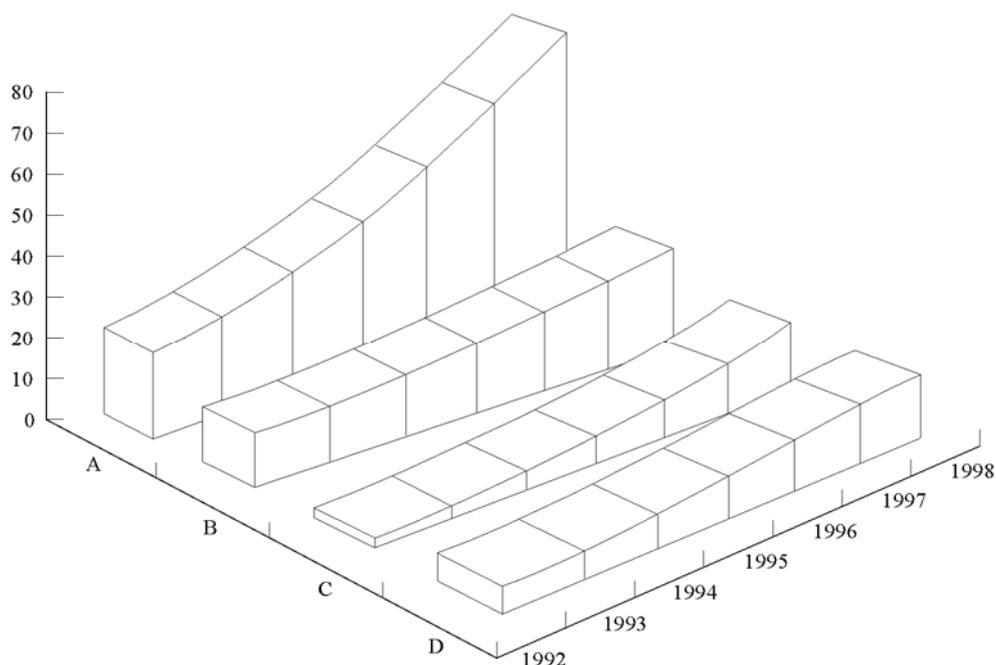
Fig. 6. Past and projected market segment trends (1992–1998), in megawatts, where A represents rural applications; B, industrial; C, utility grid-tie; and D, consumer/special.

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