SOLAR ENERGY, PHOTOVOLTAIC CELLS

1. Introduction

Photovoltaic cells, or solar cells, are solid-state devices that convert light into electricity via the photovoltaic effect. Solar cells are utilized to convert sunlight into direct current (dc) electricity, which can be used to operate a dc load, charge a battery for future use, or to run an inverter, which turns the dc into alternating current (ac), to directly run ac appliances or to feed electricity into the utility grid.

Starting with the Vanguard program in the 1950s, photovoltaic (PV) cells have been utilized to provide electricity for space satellites. In the 1970s, PV was recognized as an excellent power source for remote sites, leading to the development of a terrestrial PV industry. Since ~ 2 billion people in the world live in homes that are not connected to the power grid, the market for off-grid electricity has continued to grow. In addition, PV offers the potential for large-scale production of grid-connected electricity in the industrialized countries. Large-scale grid connect PV includes both large commercial systems as well as large numbers of smaller residential size systems. Photovoltaic cells produce renewable electricity with no pollution and with an energy payback time between 1 and 3 years depending on the technology and the operation site (1,2).

2. How a Photovoltaic Cell Works

The PV effect occurs in semiconductors, where there are distinct valence and conduction bands. While many different types of PV cells are possible, this explanation will utilize a silicon based p–n junction partly because it is one of the simplest systems and partly because this technology dominates the commercial PV business worldwide. Each atom in a silicon crystal lattice is surrounded by and bound to its four neighboring atoms. The outermost shell of electrons of each silicon atom contains four valence electrons. Each of these four valence electrons is bonded covalently to one of the nearest neighbors, sharing one of the electrons from that atom. When there is no lattice energy at absolute zero, all of the valence electrons are tightly bound, so there are no free electrons, and therefore no electrical conductivity (Fig. 1**a**). However, at room temperature there is enough thermal energy to break some of the covalent bonds and to lift a small number of electrons into the conduction band (Fig. 1**b**). The energy required to break the covalent bond and raise an electron into the conduction band is the bond energy or the band gap, E_g. In silicon, the band gap is 1.1 eV.

When an electron is excited into the conduction band, it leaves behind a hole. Neighboring valence electrons can jump into this hole, resulting in the movement of the hole in the opposite direction to the actual electron flow. Although the hole is not a concrete physical entity, it can be described as such in order to keep track of the motion of the valence electrons. Since electrons and holes move in opposite directions under an applied electric field, a hole has the same magnitude of charge as an electron, but is opposite in sign.

Light is also capable of providing the energy to break the bonds of silicon valence electrons. Each photon of light has an energy equal to the product of its frequency and Planck's constant, ie, $E = h\nu$, where E is the photon energy, h is Planck's constant, and ν is the frequency of the light. When the photon has more energy than the band gap of the semiconductor, E_g, it can be absorbed by the silicon lattice, with the photon breaking the covalent bond, and therefore injecting an electron into the conduction band and leaving a hole in the valence band (Fig. 2**a**). The conduction electron is a mobile, negatively charged carrier, while the hole is a mobile, positively charged carrier. If our semiconductor was a perfect crystal, the free electron and free hole could survive for a long time as they could only recombine with themselves. However, in a real semiconductor there are a large number of recombination sites caused by structural imperfections and impurities. For example, at room temperature the lifetime of such a free electron–hole pair is typically on the order of a few microseconds for cast multicrystalline silicon and up to a few milliseconds for high quality float zone silicon. So the generation of a free electron–hole pair by a photon is a temporary state, and the photogenerated electron and hole will recombine by either releasing a small amount of thermal energy or by emitting a photon and returning the system to equilibrium.

If the semiconductor is now continually illuminated with light, whose photons have energy above the material's band gap, a continuous generation of conduction band electrons and valence band holes will occur (Fig. 2**b**). While these free electrons and holes are continually recombining as long as there is a light induced generation of free carriers, their density will be higher than the nonilluminated density. This photoinduced increase in free carrier density produces an increase in conductivity, called photoconductivity. Photoconductivity can be a useful property in its own right, eg, as a light sensor or detector. However, energy (or electricity) can only be obtained from an illuminated semiconductor by separating the excess electrons from the excess holes to generate a voltage.

Separating the electrons and holes requires the formation of a junction. The junction can be of four different types: (*1*) A p–n junction between two doped semiconductors; (*2*) Schottky junction formed by direct contact between a metal and a semiconductor; or (*3*) metal–insulator–semiconductor (MIS) junction, where a thin insulator is sandwiched between a metal and a semiconductor; and (*4*) a heterojunction between two different semiconductors. Most commercial PV cells use p–n junctions so this structure will be used in the following explanation.

The silicon discussed above contained only silicon atoms with each of the four (4) valence electrons shared with the four (4) nearest neighbors. If a material with a valence greater than silicon is incorporated into the silicon lattice the extra valence electrons (any > 4) will be very loosely bound in the valence band. It will only take a small amount of thermal energy to inject the extra electrons into the conduction band. Using the example of phosphorous, antimony, or arsenic (each with five valence electrons), the single extra electron is very weakly bound to the lattice (0.044 eV for P, 0.039 eV for Sb, and 0.049 eV for As). So at room temperature each dopant atom will donate one free electron to the material. A silicon crystal with added donor dopants is called an n-type (negative) silicon

(Fig. 3**a**). These dopant atoms are very effective at reducing the resistivity. Intrinsic silicon with no dopant is $\sim 5000\,\Omega$-cm. It only takes phosphorous atoms at a concentration of 5×10^{15} atoms/cm^3 (or ~ 10 ppb) to reduce the resistivity to $1\,\Omega$-cm.

When a silicon crystal is doped with atoms of an element having a valence of < 4, eg, boron, aluminum, or gallium, each with a valence of 3, only three of the four covalent bonds of the nearest-neighbor silicon atoms can pair with the dopant atom's valence electrons. The vacancy at the unoccupied bond is a hole. This hole is very weakly bound to the lattice (0.045 eV for B, 0.057 for Al, and 0.065 for Ga). So, at room temperature each dopant atom will donate one free hole to the material. Dopants that contribute holes, which act like positive charge carriers, are acceptor dopants and the resulting material is called a p-type (positive) silicon (Fig. 3**b**).

Conductivity in doped silicon is determined by the properties of the additional dopant atoms, resulting in added charge carriers. In n-type silicon, electrons are the majority carriers and holes are the minority carriers. In n-type silicon, there are fewer holes than in undoped silicon because there are more majority electrons to recombine with the minority holes. (The product of n times p remains constant.) 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 recombination of some electrons with the increase population of holes.

When two different types of semiconductors (n and p type) are brought together to form a junction, there are initially mostly electron free carriers on the n-side and mostly free hole carriers on the p-side. Electrons and holes diffuse across the junction in opposite directions. In the region away from the junction, donor and acceptor ions are neutralized by the presence of free charge carriers. The zone immediately adjacent to the junction is depleted of free charge carriers and is called the depletion region. The width of the depletion region is inversely proportional to the concentration of dopant atoms. Since the depletion region has unneutralized donor and acceptor atoms, there is a separation of charge and a resultant electric field. This field causes an electrostatic or barrier potential, V_b, across the junction. Figure 4 shows the simplified band gap of the p–n junction under equilibrium conditions with the n-region to the left and the p-region to the right. The upper curve represents the conduction band, E_c, with its free electrons. The lower curve represents the valence energy band, E_v, with its free holes. The cell's band gap energy, E_g, is the energy difference between the valence and conduction band. The dotted line represents the Fermi energy level, E_F, the energy level at which the probability of occupancy of an electron state is 50%.

As seen from this band diagram, electrons can flow freely "downhill" from the p-region into the n-region, but to flow from the n-region into the p-region they must go over the energy barrier, eV_b. Likewise, the holes can flow freely "uphill" from the n-region into the p-region, but to flow from the p-region into the n-region they must go over the energy barrier, eV_b. Under normal operating conditions for a solar cell, almost all of the valence electrons from the dopant atoms in the n-region have been ionized and have become conduction band electrons. Likewise, in the p-region almost all of the holes associated with the acceptor atoms are ionized and have become free holes. The number of majority carriers (electrons in the n-region and holes in the p-region) is generally determined by the respective dopant concentrations. Changes in majority carrier concentrations due to temperature or even light excitation are typically small compared to the levels created by doping. On the other hand, the number of minority carriers in both the n- and the p-region, is sensitive to thermal and light excitation.

Light with energy greater than the band gap of the semiconductor, creates equal numbers of holes and electrons, making only a fractional change in the majority carrier density while increasing the minority carrier density by many orders of magnitude. In the n-region, this creates a large excess of minority carrier holes. If these stay in the n-region they will ultimately recombine. However, if they diffuse to the junction, they will flow "uphill" into the p-region where they are majority carriers and will not recombine. Likewise, in the p-region the light generates a higher level of minority carrier electrons. If these stay in the p-region they will ultimately recombine. However, if they diffuse to the junction, they will flow "downhill" into the n-region where they are majority carriers and will not recombine. This flow of electrons into the n-region and of holes flowing into the p-region represents a separation of charge, producing an electric field (Fig. 5). This electric field is called a Photovoltage. Its formation is shown in the band diagram of Fig. 6. The voltage increases until the electric field is large enough to stop any additional electrons from flowing to the n-region and holes flowing to the p-region across the junction. The theoretical maximum open circuit voltage, V_{oc}, of the junction is the energy barrier V_b.

The junction in Figs. 5 and 6 can deliver electricity (and energy) to a load connected across the p–n junction. Electrons will flow from the n-region through the load circuit into the p-region, where they will recombine with free holes. This process will continue as long as the light continues to generate electron–hole pairs.

3. Spectrum and Band Gap

The performance of a PV device depends on the spectrum of the light under which it is operating. On earth, the energy received from the sun spans a spectrum of wavelengths, determined by the sun's temperature and by the absorption and scattering in the earth's atmosphere. Outside of the earth's atmosphere, the spectrum, called air mass zero (AM0) is well know and fairly stable. On earth, the spectrum changes continually as a function of location, time of day, and weather. In order to provide a set of common conditions at which to rate PV devices, a standard set of test conditions have been established. Terrestrial PV cells and modules are typically rated for their maximum power output under Standard Test Conditions (STC) defined as an irradiance of $1000\,W/m^2$, the AM1.5 spectrum, and a junction temperature of 25°C. The AM1.5 spectrum is a tabulated spectrum that is an attempt to duplicate the naturally occurring spectrum under bright sunny conditions. The standard AM1.5 spectrum is shown in Fig. 7 (3). Almost all commercial PV products will be rated for peak power under STCs, but overall performance that is energy collection will depend on how the device operates under a variety of normal terrestrial conditions.

A PV material cannot utilize all of the energy of the light incident on it. Photons that do not have enough energy to lift a valence band electron across the energy gap into the conduction band, do not contribute to electricity generation. These photons either pass right through the material, or if absorbed, just produce heat. On the other hand a single photon with sufficient energy to create an electron–hole pair, typically only produces one electron–hole pair. Any extra energy in the photon above the band gap goes to heating the material. The optimum band gap for the AM1.5 spectrum is $\sim 1.45\,\text{eV}$. The GaAs, InP, and CdTe compounds have band gaps close to 1.45 eV, so they should exhibit the highest single junction efficiencies, slightly in excess of 30%. Crystalline silicon has a band gap $\sim 1.1\,\text{eV}$, with a theoretical maximum efficiency for a single junction, crystalline silicon solar cell of ~ 28–29% (4,5).

By stacking junctions of varying band gaps, higher efficiencies can be achieved. In one approach, solar cells with different band gaps are stacked in tandem so that the cell facing the sun has the largest band gap. The top cell absorbs all of the photon at or above its energy gap and transmits less energetic photons to the cell(s) below. The next cell has a lower band gap than the top cell. It absorbs all the photons reaching it that have energies at or above its energy gap and transmits the rest downward to the cell(s) below it. In principle, any number of cells could be used in tandem. The efficiency of three-stack cells has already exceeded 37% using the AM1.5 spectrum at concentration ratios between 10 and 175 suns (6).

4. Photovoltaic Materials

A number of different materials can be utilized for PV cells. These will be discussed in these general categories: crystalline silicon, other crystalline materials, thin films, and third generation materials.

4.1. Crystalline Silicon Materials. Crystalline silicon materials were the first utilized for solar cells with the initial research performed in the 1950s by Bell Laboratories and they were first commercialized in the 1960s for space applications and in the 1970s for remote power terrestrial applications. Crystalline silicon technology is also the dominate commercial PV material, as $>90\%$ of all terrestrial PV modules produced in 2004 utilized crystalline silicon substrates. Three different types of crystalline silicon materials are being used in commercial PV devices: single crystal, cast multicrystalline, and sheet or ribbon.

Single Crystal Silicon. The earliest research and commercial solar cells all used single-crystal silicon substrates, the same material utilized by the semiconductor industry. In this technology, a single-crystal seed is dipped into a bath of molten silicon. As the seed is withdrawn, the silicon grows the same orientation as the seed. The Czochralski (CZ) process is shown in Fig. 8. Initially in the 1970s, PV manufacturers like Solarex Corporation used reject or surplus semiconductor wafers to make solar cells. Later on (in the 1990s) others like AstroPower (now GE Solar) purchased semiconductor test wafers and recycled them. As PV grew there, were not enough reject or test wafers available, so PV manufacturers like Arco Solar (now Shell Solar) began to grow their own CZ crystals to specifications for PV. Wafer sizes have increased from 2 in.

(5.08 cm) rounds in the early 1970s to pseudo-square 12.5×12.5 cm in 2004. Over this same time frame, wafer thicknesses have been reduced from 350 to 400 μm to < 300 μm to save silicon. In 2004, approximately one-third of all the terrestrial PV products produced worldwide utilized single-crystal silicon substrates. The cells in these modules typically exhibit 15–20% conversion efficiency depending on the cell process utilized, while small area laboratory cells in excess of 24% have been reported (6).

Cast Multicrystalline Silicon. Cast silicon is frozen out via direction solidification in a crucible or mold as shown in Fig. 9. Cast multicrystalline Si material typically does not have as high a minority carrier lifetime as the single-crystal material, but the lower processing cost and inherent square shape leads to lower overall PV module costs. This technology was pioneered in the late 1970s and early 1980s by a number of companies including Solarex Corporation (now part of BP Solar) in the United States and Wacker in Germany.

The resultant square cast block is then sized to the desired wafer dimension and sawn into wafers typically using wire saws. Wafer size has increased from 10×10 cm in the early 1980s to a commercial standard of $\sim 15 \times 15$ cm in 2005, with some manufacturers now offering 20×20-cm wafers and cells for sale. Wafer thicknesses have been reduced from ~ 300 to < 250 μm by some manufacturers to save silicon feedstock. In 2004, 55–60% of all the terrestrial PV modules produced worldwide utilized cast multicrystalline silicon substrates. Commercial cells typically exhibit conversion efficiencies of 14.5–16.5%, while small area laboratory cells in excess of 20% have been reported (6).

Ribbon or Sheet Silicon. One attractive cost-reducing approach for PV is to grow good quality crystalline sheets directly from molten silicon. Figure 10 shows one ribbon growth technique. Grown sheets require little or no cutting or surface preparation and incur little waste of silicon feedstock. Mobil Solar (now Schott Solar) developed and commercialized the edge-defined film fed (EFG) technique (7), while Evergreen Solar developed and commercialized string ribbon technology (8). The ribbons are generally polycrystalline or multicrystalline. Contact with the dye during growth and lack of impurity segregation into the melt often result in the incorporation of impurities into the ribbon, as well as requiring the use of higher purity feedstock than is used in casting. Bulk material passivation is necessary in order to increase cell efficiencies, although ribbon cells are still somewhat lower in efficiency than single-crystal silicon cells. Those commercializing ribbon hope that by eliminating the wafering process they can save enough cost to justify the added capital cost and slower processing rate of the ribbon. Commercial cells typically exhibit conversion efficiencies of 13–15%, while small area laboratory cells of 17–18% efficient have been reported (9).

Another route to produce ribbon or sheet silicon is to deposit it from a melt onto a substrate. AstroPower, now GE Energy, has developed a process to grow silicon sheets onto ceramic substrates. Large cells (20×20 cm) have been grown, but efficiencies remain considerably below that of other crystalline silicon technologies.

4.2. Other Crystalline Materials. Single-junction crystalline solar cells can also be made using Group 3–5 (III–V) compounds, eg, GaAs, InP, and even GaInAsP. These are direct band gap semiconductors, so they are strong absorbers of sunlight. In addition, their band gaps are closer to the ideal for terrestrial sunlight. However, these materials and cells are much more expensive than silicon cells, so their use has been restricted to use in space and for concentrator applications. Single junction GaAs cells (with an AlGaAs heterojunction window layer) have been reported with STC efficiencies in excess of 25% (6). The InP cell is not far behind with a reported STC efficiency for a single-junction device of nearly 22% (6). Various combinations of 2 and 3 stack Group 3–5 (III–V) cells have been fabricated for concentrator applications with numerous groups reporting efficiencies $> 30\%$ at concentrations from 10 to 350 suns (6).

4.3. Thin Films. In the thin-film approach, the various layers of a PV device are deposited directly onto a substrate or superstrate. The advantages of thin films are the potential ability to

- Dramatically reduce the amount of material utilized. In some cases, the active semiconductor only needs to be a fraction of a micron thick in order to absorb most of the incident sunlight.
- Directly integrate into a higher voltage module, thereby eliminating much of the handling and labor now necessary to produce crystalline silicon modules.

However, thin films have several disadvantages including the following:

- Lower conversion efficiency.
- Greater susceptibility to degradation in outdoor use especially those where the semiconductor is deposited onto the glass superstrate because they now become susceptible to ion flow in the glass (10).
- Lack of experience scaling to the larger sizes (at least a square meter) in volume production.

In 2004, $< 10\%$ of all commercial shipments of PV worldwide were made using thin-film technology.

There are three major thin film PV technologies under commercial development.

1. Amorphous Silicon: Amorphous alloys made of thin-film hydrogenated silicon (a-Si:H) can be deposited on either glass superstrates or flexible metallic substrates. Because of the low minority carrier lifetimes in doped a-Si, p-i-n (p-type, intrinsic, n-type) cell structures are utilized rather than normal p–n junctions. Even in undoped a-Si, the minority carrier lifetimes are short and because of the Staebler-Wronski effect, in which light induces additional electrically active defects, the thickness of individual layers must be minimized. Therefore, to achieve reasonable efficiencies, multijunctions are often utilized. A typical example is shown in Fig. 11. The maximum reported STC efficiency for small area a-Si devices is $\sim 12.1\%$ (6), while commercial module efficiencies have efficiencies in the 5–8% range. Recent efforts to combine a-Si with micro- or nonocrystalline materials show promise at improving efficiencies and reducing the light induced degradation.

2. Cadmium Telluride: Cadmium telluride is a well-known semiconductor often used in high performance infrared (ir) sensors. The CdTe absorbs visible light very strongly, so very thin films (1–2 μm) are sufficient to absorb most of the sunlight. Small area thin-film CdTe solar cells have been fabricated with STC conversion efficiencies of 16.5% (6). Large area monolithically integrated CdTe modules have been fabricated with STC efficiencies in excess of 10% (11).

   CdTe technology is attractive because of the potential for low cost manufacturing using electrodeposition, spraying, and screen printing, all nonvacuum processes that are less capital intense than many thin-film deposition processes that do rely on vacuum. Given the potential low manufacturing costs and the reasonably high conversion efficiencies, CdTe has attracted the interest of commercial companies. First Solar is selling commercial CdTe PV modules and is rapidly expanding its production facilities. However, the toxicity of the cadmium has convinced some manufacturers, like BP Solar, not to commercialize CdTe PV modules.
3. Copper Indium Diselenide (CIS) and Copper Indium Gallium Diselinede (CIGS): Both $CuInSe_2$ (CIS) and $Cu(InGa)Se_2$ (CIGS) are ideal PV absorber materials. The band gap is near the optimum for terrestrial PV and they exhibit strong optical absorption so that very thin films ($\sim 1\,\mu m$) are sufficient to absorb most of the sunlight. The grain boundaries and surfaces in CIS and CIGS are electronically benign, so simple polycrystalline films yield reasonably high efficiency PV devices without complex grain boundary passivation processing. The defect chemistry in CIS and CIGS is such that the compositional tolerances are high, so tight process tolerances are not required. Typical CIS and CIGS cells use thin CdS layers to form p–n junctions, molybdenum for ohmic contacts to the CIS or CIGS, and transparent conductors like zinc oxide and indium–tin oxide for contact to the CdS and as an antireflective coating. While CIS and CIGS are attractive PV materials, it has taken a long time to move from the laboratory to commercialization. The two reasons for this appear to be the difficultly in scaling to larger sizes and larger volumes and sensitivity to environmental stresses. The production issues relate to uniformity of the deposited films. Reliability issues relate to the humidity sensitivity of the contacts necessitating hermetic sealing to achieve long-term life. The highest reported cell efficiencies for thin films (19.5% at STC) have been achieved on CIGS (6). Large area CIGS modules are being produced commercially at average efficiencies of $\sim 10\%$ (12). Shell Solar, Wurth Solar, and Global Solar are commercializing CIS or CIGS.

4.4. Third Generation PV. Third generation cells refer to new PV technologies that will allow high performance thin-film solar cells to be produced at low costs. These third generation cells may utilize new nanostructured or organic materials that could attain high conversion efficiencies ($> 60\%$) by utilizing phenomena, such as hot carrier collection, multiple carrier generation (impact ionization), or new semiconductors containing multiple energy levels. Examples of third generation PV technologies are (*1*) Dye sensitized cells based on dye-coated oxide (eg, TiO_2 or ZnO) absorbers separating two photo inactive materials, either electrolyte or solid state. (*2*) Organic PV cells with two interpenetrating phases (either both polymers or one polymer and C60). (*3*) Quantum dot cells where very small nanoscale semiconductor particles are embedded into a disordered or ordered matrix. The particles are so small that quantum mechanical effects determine the band structure, and therefore the interaction with light.

The best efficiencies obtained to date with dye-sensitized solar cells is $\sim 11\%$ in small-area laboratory cells (6), while the best organic solar cells are $\sim 5.7\%$ efficient (13). Recently, nanostructured solar cells have been fabricated with conversion efficiencies of 3% by synthesizing rod-shaped crystalline nanoparticles of cadmium selenide and cadmium telluride.

4.5. Commercial PV Technologies. A number of the PV technologies discussed above have now been commercialized. Table 1 indicates which PV technologies have been commercialized by which manufacturers. The list is arranged approximately by volume of shipments in 2004 with the company that shipped the most volume of product on the top to the company that manufactured the least volume in 2004 on the bottom.

5. Photovoltaic Devices

The simplest solar cells use a diffused p–n homo-junction of crystalline silicon with screen printed contacts on the front and rear as shown in Fig. 12. To increase cell efficiencies cells often include the following:

- Antireflective coatings (AR) and/or front surface texture etching: Bare silicon reflects $\sim 35\%$ of the solar spectrum. A simple single layer AR coating of a high index material, such as Ta_2O_5, TiO_2, or SiN can reduce the reflection to $< 10\%$.
- Front Surface Passivation: Treating the front surface with PECVD SiN or thermal oxidation can reduce the defect states at the surface itself and in the case of PECVD SiN even provide hydrogen for passivation of bulk defects (14).
- Back Surface Field: Alloying with Aluminum or diffusion of boron into a p-type base can add a p^+ region to the rear of the cell which improves collection of the minority holes and screen the minority carrier electrons from recombination at the back surface.

BP Solar, Kyocera, Sharp, Q-cells, and Shell Solar all produce screen printed cells with most if not all of these properties.

A number of commercial cell manufacturers have utilized specialty structures in order to increase cell performance. Several examples are

- University of New South Wales developed and BP Solar (Madrid) commercialized as the Saturn cell the laser grooved buried contact cell (LGBC) (15). In this structure, the front metallization is buried in laser grooves as shown in Fig. 13. This structure reduces shadowing of front surface contacts and decouples the light emitter diffusion from the heavy diffusion under the metal (a selective emitter), producing commercial cells with average efficiencies in excess of 16%.

- SunPower and Advent Solar are commercializing cells with all of the contacts on the back of the cell as shown in Fig. 14. This cell structure eliminates front surface shadowing and can provide improved collection of the high currents associated with large area cells. However, this cell structure requires silicon substrates with very high lifetimes (usually float zone or magnetic CZ) and excellent front surface passivation. SunPower claims their commercial cells exhibit conversion efficiency in excess of 20% (16).
- The HIT (Heterojunction with intrinsic thin layer) cell uses heterojunctions between a-Si and crystalline silicon as shown in Fig. 15. The heterojunction produces a much higher voltage than the standard p–n junction so HIT cells have high efficiency with 21.5% reported on 100 cm^2 (17) and commercial modules available from Sanyo with reported cell efficiencies of 18.5%.

6. Photovoltaic Modules

Photovoltaic modules consist of one or more solar cells electrically connected together, supported by a substrate or superstrate, and encapsulated to protect the cells and the conductors from the environment. The module is intended to produce electricity for many years, and therefore must be designed to operate outdoors over a wide range of weather conditions for many years. Today most commercial PV modules carry 25-year warranties.

The construction of a typical crystalline silicon module is shown in Fig. 16. It consists of the following:

- Solar cells electrically interconnected together using copper ribbon or wire soldered or otherwise attached to the cells.
- A low iron, tempered glass superstrate.
- A polymeric encapsulant such as ethylene vinyl acetate (EVA) to protect the cells and bond them to the glass.
- A backsheet, such as Tedlar–Polyester–Tedlar to prevent moisture intrusion and to provide for high voltage stand-off.

One of the advantages of thin-film technologies is the potential to integrate the entire module construction onto the substrate or superstrate. The concept is illustrated in Fig. 17 where laser scribing and vacuum evaporation of the back contact metal provides the isolation and series interconnection of individual cells on the glass superstrate.

The direct deposition of the semiconductors onto the substrate or superstrate can result in problems associated with current flow through the material on which the semiconductor has been deposited. Thin films tend to be more susceptible to moisture induced corrosion than crystalline silicon. In some cases, this is just because there is much less material available in the thin-film products. In other cases, it is due to the deposition process that results in higher surface areas, and therefore more reaction. Finally, some of the thin-film materials are inherently less tolerant of corrosion remembering that crystalline silicon forms a protective oxide during processing. Therefore, it is often necessary to provide a hermetically sealed package for thin-film modules.

The commercial success that PV has achieved is in large part due to the proven reliability and long lifetime of crystalline silicon modules. Outdoor field testing has been used to identify failure mechanisms that can be evaluated using accelerated stress tests, eg, thermal cycling and damp heat exposure [see, eg, IEC 61215 (18)]. Recent BP Solar work on crystalline silicon PV module field returns indicated a rate of failure of one module per 4200 module years of operation (19,20). Because of all the work on PV module reliability, PV modules are usually the most reliable part of the system (21,22).

7. Balance of System Components

In addition to PV modules, a PV system requires mechanical support structures for the modules, wiring to connect the modules to the control electronics and or the load and electronic safety components, such as fuses and blocking diodes. A stand-alone system usually includes a charge controller and batteries for storage. The batteries are typically the shortest lifetime component in the system. Even when deep discharge batteries are used, they cannot be expected to last 25 years like the module. In many cases in the third world, batteries are locally sourced to reduce cost. Often these are not deep discharge batteries so the batteries only survive for a few years. In addition, the majority of short-term reliability issues involve the charge controller that can fail prematurely or just have its set points wrong so that the system will not function correctly.

In a grid connect system, there is usually an inverter that includes a maximum power point tracker for the PV array and a dc to ac converter. Inverter problems are the major cause of downtime for grid connected PV systems. Inverter reliability issues include heat dissipation, exposure to the weather and grid transients.

8. Commercial History of PV

The initial commercial manufacture of solar cells provided power systems for US satellites. In the 1970s, a terrestrial PV business developed to provide power systems for remote applications. Initial remote or standalone applications include communications and telecommunications; navigation aids; cathodic protection; remote sensors and relays; instrumentation; lighting; water pumping; remote homes and village power; and watches and calculators.

In these remote site applications, PV was cost effective even at the \$20/Wp cost for modules in the mid-1970s, and so PV soon became the technology of choice for them.

Over the last 20 years the commercial PV business has grown 20–25% per annum. The growth in shipments over the last 11 years is shown in Fig. 18. Until the early 1990s, this market growth was driven almost entirely by growth in the remote site applications. However, starting in the mid-1990s the grid connected market has become an increasing share of the overall PV market. By ~ 1998 the grid-connect market surpassed the stand alone market in volume of sales. Since 2002, the PV market has grown dramatically, doubling in the 2 years between 2002 and 2004.

The growth in grid-connect systems is being driven by government supported programs in Japan, Europe (particularly Germany, where "green" governments have subsidized the deployment of renewable energy systems including PV rather than building more fossil fuel power plants) and several U.S. states, particularly California and New Jersey. These programs typically start by cost sharing a large percentage of the cost of the PV system and then slowly reduce the percentage of cost sharing as the price of the systems comes down.

Japan has been the largest PV market in the world over the last 5 years. It is instructive to review the Japanese program in more detail to understand how and why it has been so successful. Japan has an acute shortage of domestic sources of energy. In 1994, The Ministry of Economy, Trade and Industry (METI, formerly called MITI) launched a subsidy program for residential PV systems with an overall goal of installing 4.82 GW of PV generation by 2010. In 1994, the program was launched with a subsidy of 50% of the cost of the PV system. The program attracted homeowners not only because of the subsidy, but also because the residential electricity rates in Japan are ~ 24 Yen/kWh (~ $0.24/kWh) among the highest residential rates in the world. Mortgage interest rates in Japan are low (1–2%) and were extended to cover the costs of residential PV systems.

Since 1994 the Japanese PV market has grown by 30% a year even thought the subsidy level has been reduced every year. By 2003, the Japanese market represented > 40% of the world's PV demand. By FY 2004, the residential subsidy has been reduced to 6.6%, but the number of participants has continued to grow every year.

Germany has used a different approach to subsidizing PV systems. Rather than assist with the initial purchase as done in Japan, the German program pays a rate or tariff based incentive. In this approach, the PV system owner is paid a specified rate for the kWh produced by the PV system. While such a program had been on going in Germany since the late 1990s, a change in the structure of the incentive program that began in 2004 resulted in explosive growth of the German PV market in 2004 and 2005. The feed in tariff rates were established at 45.7 Euro ¢/kWh for ground mounted systems (with a 6.5% annual reduction), at 57.4 Euro ¢/kWh for rooftop residential and at 54.6–54 Euro ¢/kWh for rooftop commercial (with a 5% annual reduction). In addition to the feed in tariff, preferential loans are available for PV because of the CO_2 lowering potential. In Germany, the incentive for PV has gone from environmental to economic with financial returns of 6–12% predicted. In 2004, the German PV market more than doubled, over taking Japan as the world's largest PV market with ~ 34% market share. This dramatic market growth was actually constrained in late 2004 and 2005 by lack of module availability.

The United States represented 10–12% of the world PV market in 2003 and 2004. The vast majority (>80%) of this product went to California because of the state incentive programs. In 2004, New Jersey established an aggressive incentive program and shipments to that state have shown significant growth. A number of European countries (Spain, Italy, and Portugal) have recently implemented incentive programs and the markets in these countries are expected to grow rapidly in the near future. In the rest of the world, the two giants, China and India, are both utilizing PV for large rural electrification programs.

A number of lessons can be learned from the Japanese and Germany PV programs. The first is that major PV markets can be driven by public policy support. However, success requires a long-term view with stable policies. Japan and Germany both started their programs in the 1990s. Substantial investments are required as both Japan and Germany have invested several billion US dollars in PV development, but now have a gigawatt of installed PV to show for it as well as fast growing markets. These programs also demonstrated that the sales volume created by the incentive schemes does lead to lower costs. The incentives can be reduced as volume grows. In Japan, the buy down rate has now been reduced to < 10% of the total system cost.

9. Status of PV Business

In 2004 and 2005, the PV industry has been operating at nearly full capacity. Even in this constrained mode, the growth rate in 2004 was > 40%. In 2005, a silicon feedstock shortage has also impacted the PV industry. More than 95% of the PV products shipped in 2004 used crystalline silicon solar cells. Historically, the feedstock for these cells came as scrap from the semiconductor industry. The recent rapid growth PV has now outpaced this source of feedstock. If new sources or methods of purification are not developed, crystalline silicon PV will be restricted in growth. Efforts to develop new methods for manufacturing silicon feedstock are underway (23–25). Significant feedstock from these new sources is not expected until mid-2006 at the earliest.

Some of the important features of the PV market in 2004 and 2005 are the following:

- At least 75% of the shipments are going to grid connected systems.
- The three largest markets in the world remain Germany, Japan, and the United States.
- In a grid connected system the modules represent 40–50% of the total installed system cost.
- Solar electricity costs $0.20–0.30/kWh, depending on location of the system (without incentives).
- Because of the shortage of silicon and subsequent availability of PV modules the selling price for modules increased by > 10% in 2004, the first significant cost increase since the 1989–1990 time frame.

- The rapid growth of the PV market has provided an excellent opportunity for new thin-film technologies to gain a share of this market. Thin films have particular advantages for use in building integrated applications.
- Over the last 5 years, the PV Market segment breakdowns as grid-connect (60%), Remote Industrial (17%), Remote Habitation (22%), and Consumer (1%).
- In general if a residence is $>1\,\mathrm{km}$ from the grid lines, PV will be less expensive than grid extension.

If Photovoltaics continues to grow, it can become a significant source of electricity for the energy starved world. At the present growth rate PV would be able to provide one-third of all the new (additional) electricity required in the world by 2040.

BIBLIOGRAPHY

"Photoelectric Cells" in *ECT* 1st ed., Vol. 10, pp. 519–542, by V. K. Zworykin and E. G. Ramberg, Radio Corp. of America; "Phototubes and Photocells" in *ECT* 2nd ed., Vol. 15, pp. 396–443, by C. P. Hadley and co-workers, Radio Corp. of America; "Photovoltaic Cells" in *ECT* 3rd ed., Vol. 17, pp. 709–732, by J. C. C. Fan, Massachusetts Institute of Technology; in *ECT* 4th ed., Vol. 18, pp. 964–991, by C. F. Gay, National Renewable Energy Laboratory and C. Eberspacher, UNISUN; "Photovoltaic Cells" in *ECT* (online), posting date: December 4, 2000, by C. F. Gay, National Renewable Energy Laboratory and C. Eberspacher, UNISUN.

CITED PUBLICATIONS

1. K. Kato, A. Murata, and K. Sakuta, "Energy Pay-back Time and Life-cycle CO_2 Emission of Residential PV Power System with Silicon PV Module", *Progress in Photovoltaics*, Vol. 6, 1998, p. 105.
2. K. Knapp, T. Jester, and G. Mihalik, "Energy Balances for Photovoltaic Modules: Status and Prospects" *28th IEEE Photovoltaic Specialist* Conference, 2000, p. 1450.
3. IEC 60904-3: Photovoltaic devices—Part 3: Measurement principles for terrestrial photovoltaic (PV) solar devices with reference spectral irradiance data.
4. Martin A. Green, *Silicon Solar Cells*, Bridge Printery Pty. Ltd., 1995, p. 131.
5. R. Swanson, "How Close to 29% Limit Efficiency Can Commercial Silicon Solar Cells Become", *31st IEEE PV Specialist Conference*, 2005, p. 889.
6. M. A. Green and co-workers, *Prog. Photovolt.* **13**: 387 (2005).
7. F. V. Wald, "Crystal Growth of Silicon Ribbons for Terrestrial Solar Cells by the EFG Method", *Crystals: Growth, Properties and Applications*, Vol. 5, 1981, p. 147.
8. R. L. Wallace, R. E. Janoch, and J. I. Hanoka, "String Ribbon—A New Silicon Sheet Growth Method", *Proceedings of the 2nd WC PVSEC*, 1998, p. 1818.
9. M. Kaes, G. Halm, and A. Metz, "Bulk Passivation in Silicon Ribbon—A Lifetime Study for an Enhanced High Efficiency Process", *31st IEEE PV Specialist Conference*, 2005, p. 923.

10. D. Carlson, “Accelerated Corrosion Testing of Tin Oxide Coated Glass”, *Proceedings of NREL Thin Film Module Reliability National Team Meeting*, 2002. (NREL/CD 520-32921)
11. D. Cunningham and co-workers, “Large area Apollo^{TM} module performance and reliability”, *28th IEEE PV Specialist Conference*, 2000, p. 13.
12. M. Powalla and co-workers, *Tin Solid Films*, 2003, p. 523.
13. J. Xue, S. Uchida, B. Rand, and Stephen R. Forrest, *Appl. Phys. Lett.* **85**(23): 5757 (2004).
14. B. Sopori and co-workers, “A Comprehensive Model of Hydrogen Transport into a Solar Cell During Silicon Nitride Processing for Fire-Through Metallization”, *31st IEEE PV Specialist Conference*, 2005, p. 1039.
15. N. B. Mason, D. Jordon, and J. G. Summers, “A high efficiency silicon solar cell production technology”, *10th European PV Solar Energy Conference*, 1991, p. 280.
16. Available at www.sunpowercorp.com.
17. M. Taguchi and co-workers, “An Approach for the Higher Efficiency HIT Cells”, *31st IEEE PV Specialist Conference*, 2005, p. 866.
18. IEC 61215 ed. 2, *Crystalline silicon terrestrial photovoltaic modules- Design qualification and type approval*, 2005.
19. J. Wohlgemuth, Long term photovoltaic module reliability, *Proceeding of the National Center for Photovoltaics Review Meeting*, Denver, Col., March, 2003, p. 179.
20. J. H. Wohlgemuth, D. W. Cunningham, A. M. Nguyen, and J. Miller, “Long Term Reliability of PV Modules”, *Proceedings of 20th European PVSEC*, 2005, p. 1942.
21. J. C. Wiles, B. Brooks, and B-O. Schultze, “PV Installations, A Progress Report,” *Proceedings of the 29th IEEE Photovoltaic Specialist Conference*, 2002, p. 1461.
22. A. L. Rosenthal, M. G. Thomas, and S. J. Durand, “A Ten Year Review of performance of Photovoltaic Systems”, *Proceedings of the 23rd IEEE Photovoltaic Specialist Conference*, 1993, p. 1289.
23. D. Weidhaus, E. Schindlbeck, K. Hesse, and E. Dornberger, “Pilot Production of Granular Polysilicon from Trichlorosilane Using a Fluidized Bed-Type Reactor”, *20th European PVSEC*, 2005, p. 565.
24. A. Muller, R. Sonnenschein, T. Sill, A. Golz, and P. Adler, “New Process for Cost Effective Solar Grade Silicon from Silane”, *20th European PVSEC*, 2005, p. 623.
25. K. Peter, E. Enebakk, K. Friestad, and C. Dethloff, “Investigation of Multicrystalline Silicon Solar Cells from Solar Grade Silicon Feedstock”, *20th European PVSEC*, 2005, p. 615.

JOHN WOHLGEMUTH
BP Solar

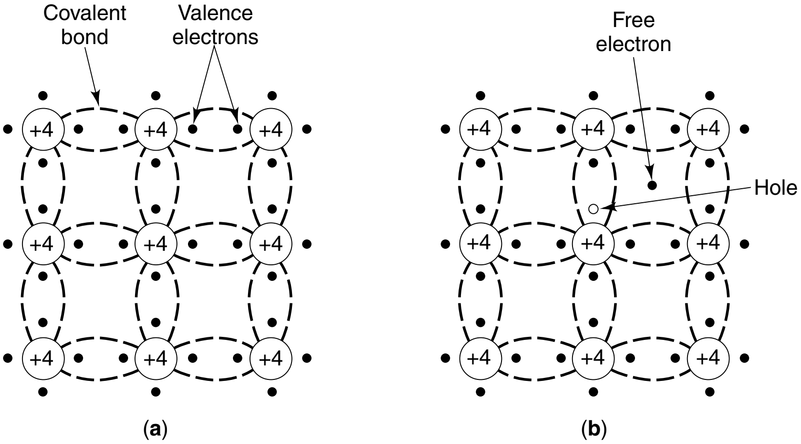

Fig. 1. (**a**) Silicon crystal lattice shown in two dimensions (2D) with all bonds made ($T = 0\,\mathrm{K}$). (**b**) Silicon crystal lattice shown in 2D with one bond broken ($T > 0\,\mathrm{K}$).

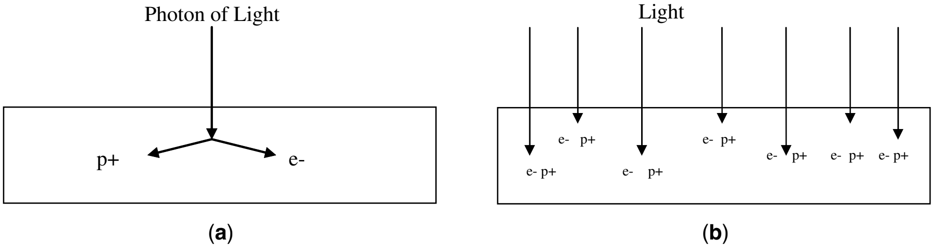

Fig. 2. (**a**) Interaction of a photon of light with a semiconductor. (**b**) Photoconductivity.

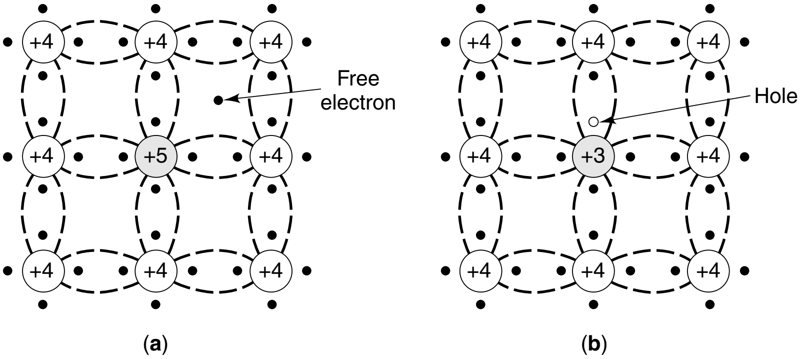

Fig. 3. (**a**) Silicon lattice with a silicon atom displaced by a donor dopant atom, n-type. (**b**) Silicon lattice with a silicon atom displaced by an acceptor dopant atom, p-type.

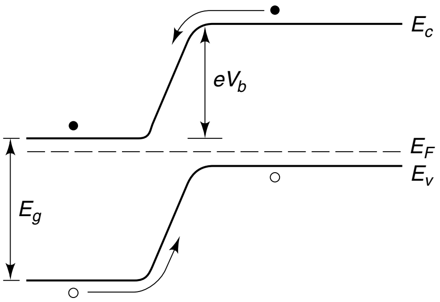

Fig. 4. Simplified band diagram of p–n junction (in the dark in thermal equilibrium).

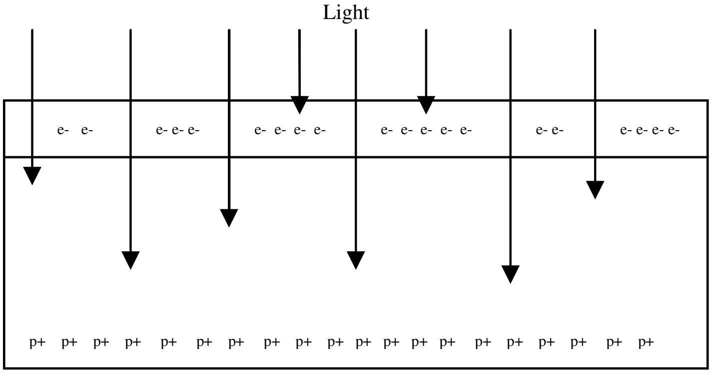

Fig. 5. Photon flux of light generates a photovoltage.

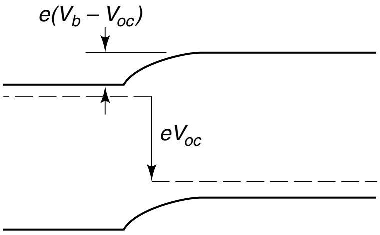

Fig. 6. Band diagram of p–n junction in sunlight under open circuit conditions.

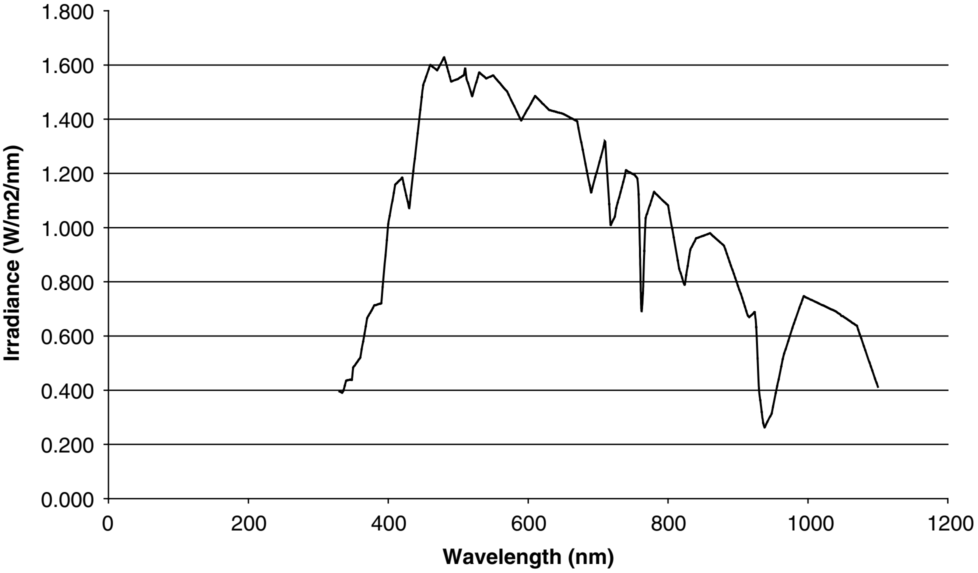

Fig. 7. Standard AM1.5 spectrum from IEC 60904-3.

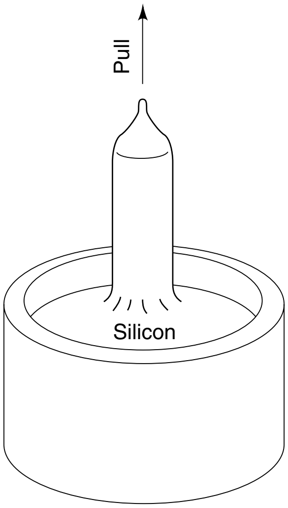

Fig. 8. Single-crystal (Czochralski) growth method.

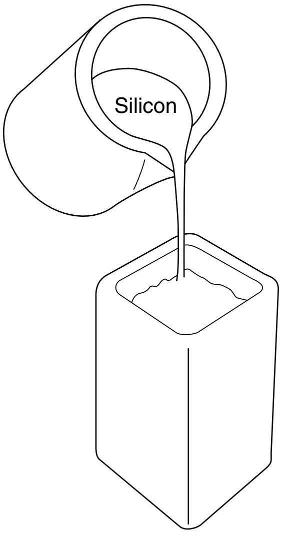

Fig. 9. Silicon casting.

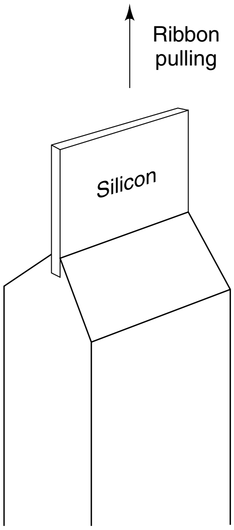

Fig. 10. Silicon ribbon growth.

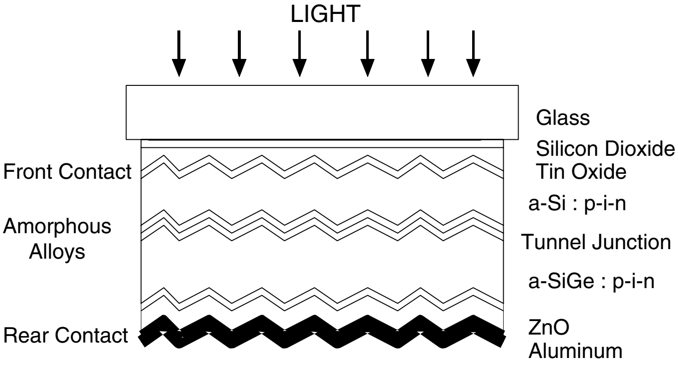

Fig. 11. Typical a-Si double junction structure.

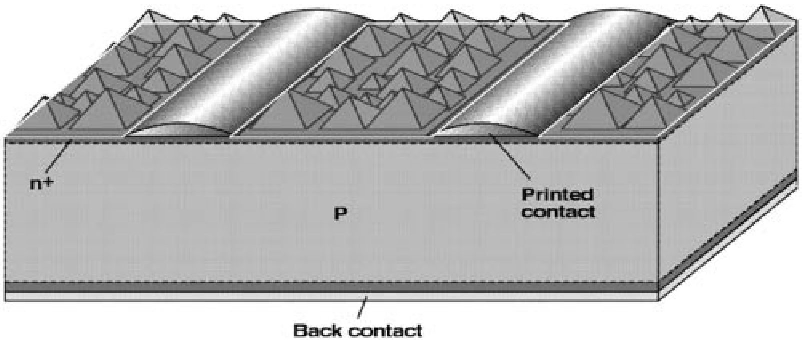

Fig. 12. The p–n junction screen print solar cell.

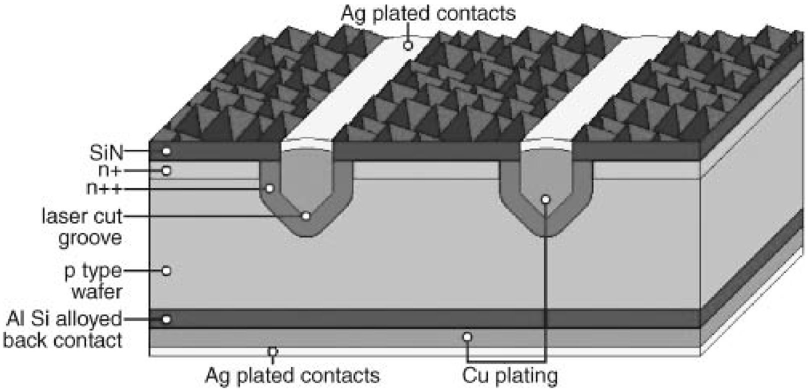

Fig. 13. Laser grooved buried contact cell.

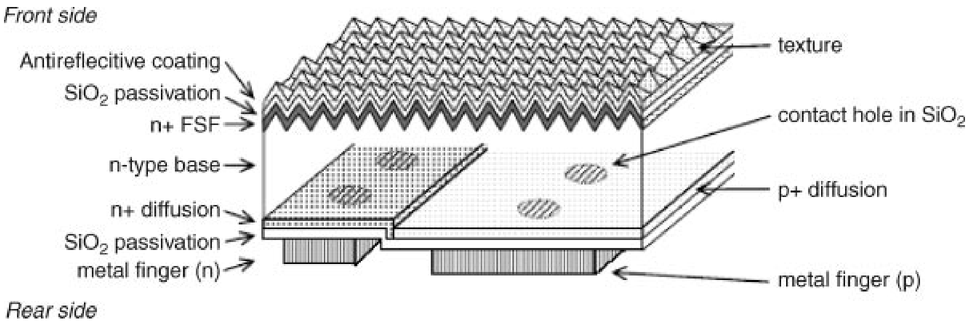

Fig. 14. Back contact solar cell.

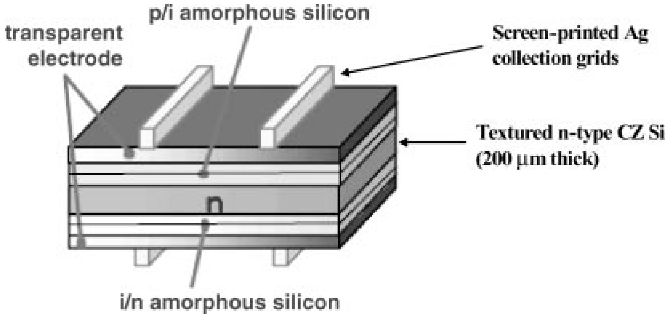

Fig. 15. Structure of the HIT cell.

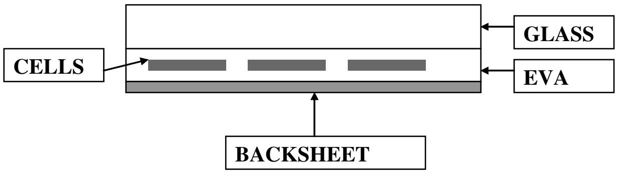

Fig. 16. Typical construction of PV modules.

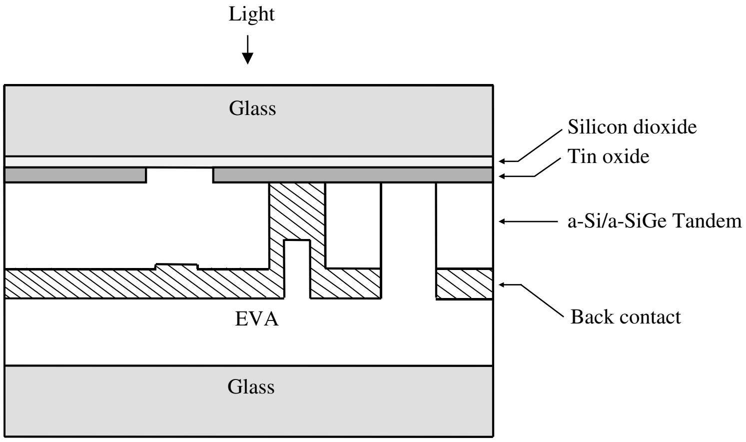

Fig. 17. Monolithically integrated thin-film module.

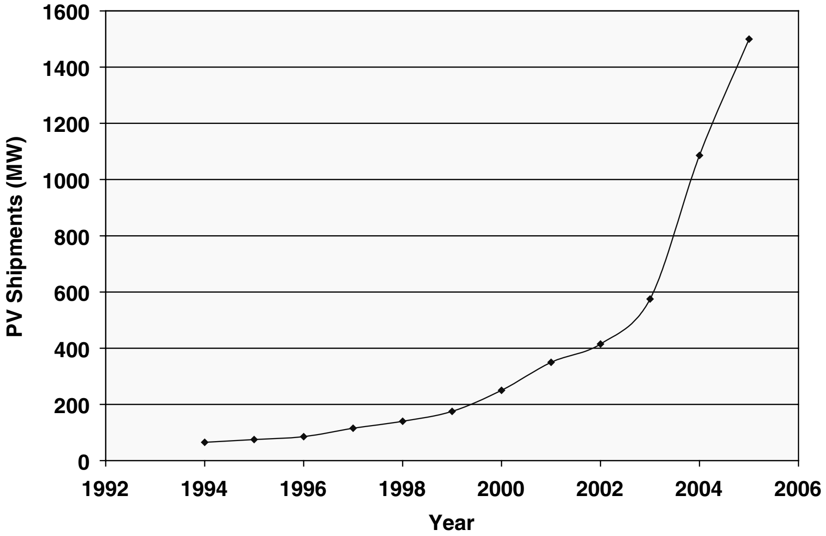

Fig. 18. Worldwide shipments of PV modules.

Table 1. **Commercial PV Companies and Their Product Technologies**

Manufacturer	Commercial Technologies
Sharp	multicrystalline silicon, CZ silicon, small amount of a-Si
Kyocera	multicrystalline silicon
BP Solar	multicrystalline silicon, CZ silicon
Shell Solar	CZ silicon, multicrystalline silicon, CIS
Q Cells	multicrystalline silicon, CZ silicon
Schott Solar	EFG silicon ribbon, CZ silicon, multicrystalline silicon, a-Si
Sanyo	CZ silicon, a-Si
Mitsubishi Electric	multicrystalline silicon
Isofoton	CZ silicon
Motech	multicrystalline silicon
Photowatt	multicrystalline silicon
GE Energy	CZ silicon, Si on ceramic sheet
Kaneka	a-Si
Uni-Solar	a-Si
Evergreen	string ribbon crystalline silicon
First Solar	CdTe
Wurth Solar	CIS
Global Solar	CIGS