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PHOTOVOLTAIC CELL TECHNOLOGIES

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ABSTRACT

The main goal of research and development on photovoltaic cells is to reduce the capital cost of electric power generation. This can be accomplished by reducing the cost of the cells and by improving their efficiency. The materials and technology of such photovoltaic cells as single crystal, polycrystalline and amorphous silicon, copper-cadmium sulfide, and gallium arsenide are reviewed. Also reviewed are innovative techniques used to increase cell efficiency including Schottky junction, shallow junction, multijunction, inversion layer and back surface field. The operation principle of semiconductor/liquid junction cells is presented. The technological development of concentrator-enhanced cells is described. The economics of photovoltaic cells is discussed, and specific present and future applications are presented.

1. INTRODUCTION

Although the photovoltaic effect has been observed in the junction of any two dissimilar materials, the primary materials used for photovoltaic converters are semiconductors. Semiconductors are a class of materials with electric conductivity somewhere between metals and insulators. Silicon is the essential ingredient in the manufacture of semiconductors and solar cells. It does not exist in single-crystal form in nature. Rather, it exists as silica, or silicon dioxide (SiO_2), a compound of the two most abundant elements in the earth's surface (almost 60% of the earth's crust is silica). Quartzite, which can be almost 99% silica in high-grade mineral deposits, is the usual starting point for producing silicon for solar cells. Other materials are not good raw materials, because they have too many impurities that are costly to eliminate. The demand for silicon has grown from 150 metric tons in 1965 to over 2500 metric tons in the last years. This level approaches the estimated total production capacity of 3000 metric tons in Western nations.

Three main directions for low cost, high efficiency silicon photovoltaic cell production are being followed: one is based on the use of single crystal material sliced from large diameter ingots; another approach employs directly fabricated sheet material of reduced quality that offers the potential for lower cost; and, the third direction is to produce silicon wafers sliced from cast polycrystalline blocks. Research work is underway on wafer surface preparation, cell junction formation, metallization, cell string assembly and automated process module assembly. Also, more than sixteen different material combinations are being investigated for thin-film cells. Thin-film cells have the advantage of

using little active material since they can absorb sunlight more efficiently than single crystal silicon. In general, the goals of the U.S. Photovoltaics Program are directed toward producing economical photovoltaic cells of high durability at factory target costs of \$700 per peak kilowatt by 1986, as compared to about \$1000 per peak kilowatt now. The performance goals of the arrays include efficiencies greater than 10%, and an expected operating lifetime in excess of 20 years.

Intensive research is being carried out on new types of cells ranging from single crystal, polycrystalline and amorphous cells to cascade cells and semiconductor-liquid junction cells. Moreover, two major photovoltaic system technologies currently under intensive development are: (1) flat-plate cells which have a power capacity of 80-120 W/m^2 , and (2) concentrator-enhanced cells, with possible capacities up to 150 W/m^2 or more, depending on the concentration ratios, optical system efficiencies, and solar cell conversion efficiencies of the specific system.

2. FLAT-PLATE TECHNOLOGY

The flat-plate technology is oriented toward development of a new process of high purity silicon production, mass manufacturing of silicon sheet, processing and fabrication of low cost and high efficiency cells and arrays. The research is being conducted on single crystal silicon and gallium cells, polycrystalline silicon and gallium cells, amorphous silicon cells and other types of thin-film solar cells. Innovative techniques to enhance cell efficiency are also being implemented.

2.1. Silicon Technology

The technology for making high purity, single crystal silicon for solar cells is well known[1]. To make a solar cell, quartzite that is 90% or more silica (SiO_2) must be refined and its impurities removed. The quartzite is heated in the presence of carbon to break the SiO_2 into elemental silicon (Si) and carbon dioxide (CO_2). Since the silicon still retains impurities originally in the quartzite, an appropriate chemical vapor is blown over the silicon to remove most of them. The gas reacts with impurities such as aluminum, carbon, and magnesium that leave as part of the gas. After this process, the silicon still retains some impurities; so, using hydrogen chloride and a copper catalyst it is converted to a liquid called trichlorosilane (SiHCl_3). The trichlorosilane is then distilled (much as are petroleum products), to separate the SiHCl_3 from the remaining impurities. Finally, the SiHCl_3 is broken down and pure silicon isolated by a slow, expensive, energy-intensive "chemical vapor deposition method" at 2680°C. Vaporized trichlorosilane

is reacted with hydrogen gas to precipitate pure silicon. The above procedure raises the cost of silicon ingots to about \$70/kg; approximately 80% of this cost occurs in the last process which reduces trichlorosilane to a high-grade silicon. This kind of silicon is a polycrystalline material made up of numerous randomly packed "grains" of single-crystal silicon. To make effective solar cells, polycrystalline silicon must be processed into the large-grained or single-crystal material used in the typical cell's base layer.

To turn polycrystalline silicon into single-crystal silicon, it must be melted at 1410°C and allowed to solidify in such a way so that the silicon atoms arrange themselves in a perfect lattice. The molten silicon is cooled very slowly while it is initially in contact with a single-crystal "seed" of silicon. As the single-crystal silicon is grown, appropriate substances, or dopants, are introduced to make the base material behave electrically in the way necessary for solar cell operation. There are a number of dopants that can be used. However, single-crystal silicon technologies have generally been developed for boron dopant in the base and phosphorus in the collector layer.

The two most established and dependable means of growing single-crystal silicon are the Czochralski process and the floating-zone technique (see Fig. 1).

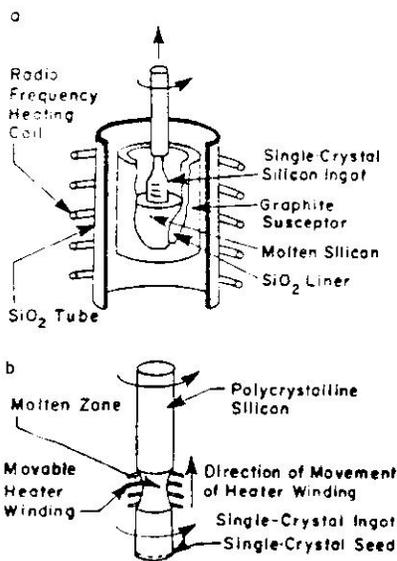


Fig. 1. Production Process of Single-Crystal Silicon [1]: a. Czochralski Growth Apparatus, b. Floating-Zone Process.

The Czochralski Process: Here, a seed of single-crystal silicon contacts the top of a molten mass of purified silicon. The seed crystal is slowly raised (less than 10 centimeters per hour) and rotated. As the crystal rises imperceptibly from the melt, silicon freezes on its surface, extending the single-crystal structure. The final product is a

long cylindrical ingot, or "boule," typically 7.5 centimeters in diameter. The silicon ingots are then cut with diamond saws to wafers about 0.5 mm thick. Since during the cutting process up to 60% of the material is lost, this contributes to the high cost of silicon cells.

The Floating-Zone Technique. This procedure requires an ingot of polycrystalline silicon and a seed crystal of single-crystal silicon. The polycrystalline ingot is placed atop the seed crystal and heated, causing the interface between the materials to become molten. While the ingot remains stationary, the heating coils are slowly raised. Single-crystal material solidifies below the molten interface and perpetuates upward as the heating coils move up. Newer processes that incorporate this strategy by producing ribbons (long, thin, rectangular sheets) of single-crystal material include: edge-defined film-fed growth (EFG), dendritic web growth, and ribbon-to-ribbon (RTR) growth.

2.2. Single Crystal Cells

2.2.1. Silicon Cell

The most normal configuration for a single crystal cell is to make a p-n junction. If the junction has the same basic crystalline material on both sides, it is called a homojunction diode. A p-n junction can also be made by bringing two different materials together, one of which is basically a p-type and the other a n-type. The energy band gap* is thus different on either side of the junction. This kind of junction is called a "heterojunction." The junction of "p-type" and "n-type" materials provides an inherent electric field which separates the charges created by the absorption of sunlight. This p-n junction is usually obtained by putting a p-type base material into a diffusion furnace containing a gaseous n-type dopant (usually phosphorous) to diffuse into the surface about 0.2 μm; ion implantation could be another means of obtaining similar results (the p-type dopant is usually

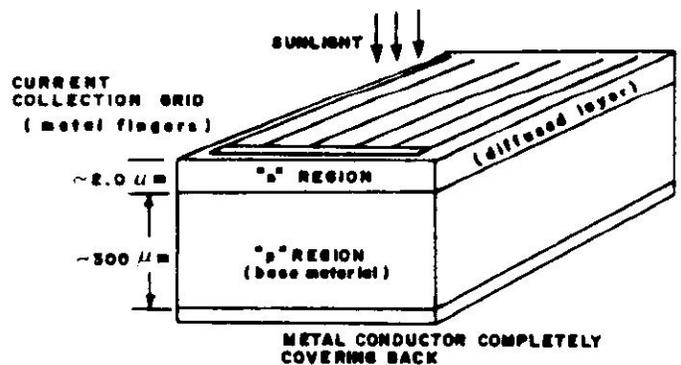


Fig. 2. Cross-Sectional View of Typical p-n Junction Cell [2].

boron). The junction is formed slightly below the planar surface of the cell and the light impinges perpendicular to the junction. The positive and negative charges created by the absorption of photons are encouraged to drift to the front and back of the solar cell. The back is completely covered by a metallic contact to remove the charges to the electrical load. The collection of charges from the front of the cell is done by a fine metallic grid. An antireflective coating is applied on the top of the cell [2]. Figure 2 shows a cross-sectional view of a typical p-n junction cell.

In general, the p-n junction, silicon solar cell is fairly well understood and efficiencies up to 18% have been obtained in laboratory conditions for single crystal, float-zone silicon wafer fabricated substrate [3]. Theoretically, silicon p-n junction cells can convert a maximum of about 22% of the energy in AM0** sunlight to electricity.

2.3.2. Gallium Arsenide Cells

Gallium arsenide (GaAs) is emerging as a very promising material for both high-efficiency single-crystal and thin-film solar cells. It is superior to silicon in several respects, except the cost. The energy band gap of GaAs, about 1.4 eV, is higher than silicon's 1.1 eV and is in the range that gives the highest theoretical conversion efficiency for a single-crystal, single-junction cell, about 26% at AM0 compared to 22% for silicon. A gallium arsenide cell which used a single crystal only 0.04 μm thick, has shown efficiency as high as 21.8%. In the high efficiency single-crystal cells, the active single-crystal layer is grown on a GaAs substrate. This technology awaits, however, further refinement and adaptation for mass production. GaAs single-crystal cells are also being used in concentrator enhanced cells because of high efficiency at elevated temperatures. Also, the efficiency of GaAs cells does not decrease with temperature as rapidly as that of silicon cells. Table I compares the performance of a gallium arsenide cell with a silicon cell.

Table I. Performance of Single Crystal p-n Junction Cells [4].

Cell Material	Absorber Energy Gap eV	V_{oc} Volts	J_{sc} mA/cm ²	Fill Factor	Max. Eff. %
Si	1.1	0.63	34.0	0.80	16.8
CsAs-GaALAs	1.4	0.99	27.3	0.76	21.8

* The energy characteristic to each material and the atomic structure at which electrons are freed upon the material being struck by photons.

** Air Mass Zero is defined as the power density of sunlight just above the earth's atmosphere and is equal to about 1350W/m².

2.3. Polycrystalline and Amorphous Cells

The concept of thin-film polycrystalline and amorphous solar cells is attracting much interest. In this process, a thin layer of semiconductor material, such as polycrystalline silicon, polycrystalline gallium arsenide, cadmium sulfide, or amorphous silicon, is deposited on an inexpensive substrate, plastic or glass. A basic thin-film solar cell can be described as having five layers: the opaque electrical contact, the photon absorber-minority carrier generator, the minority carrier collector-majority carrier converter, the transparent electrical contact, and the transparent encapsulant.

Since thin-film cells require much smaller amounts of active photovoltaic material and tolerate more imperfections in that material, their production cost is expected to be considerably lower than those achievable with single-crystal silicon cells.

The search for new thin film materials appropriate to solar cell applications is of particular importance. Features such as the electronic structures, traps, mobilities, and the characteristic optical absorption are frequently those that determine material suitability. Research is being done on such promising new thin-film materials as indium phosphide (InP), cadmium telluride (CdTe), zirconium phosphide (Zr₃P₂), and copper indium selenide (CuInSe₂). However, the most widely studied thin film cells are cadmium sulfide/copper sulfide (CdS/Cu₂S), polycrystalline gallium arsenide (GaAs), polycrystalline silicon (Si), and amorphous hydrogenated silicon(A-Si:H). Table II shows selected parameters of thin-film cells.

2.3.1. Polycrystalline Silicon Cells

A number of variables have to be controlled in preparing a polycrystalline film for a high performance cell. Some of them can be listed as: film thickness has to be optimized to account for the optical absorption depth and grain boundary recombination, grain size should be large (about 100 μm and 1 nm across) compared to the absorber layer thickness, the grain boundaries should show high resistance, epitaxy at the junction should reduce the recombination velocity at the interface, and maximize the minority carrier diffusion length in that region. These requirements are quite demanding and the proper fabrication technique for polycrystalline silicon cells has been elusive.

The polycrystalline thin-film silicon cells are grown by chemical vapor deposition on recrystallized metallurgical silicon substrates, and are about 20 to 30 μm thick with crystallites varying up to several hundred microns in lateral extent. It is expected that the cost of such cells could come down to \$1.50 per peak watt, if a cell efficiency*** of 6% and mass production could be attained.

2.3.2. Cadmium Sulfide/Copper Sulfide Cells

The cadmium sulfide solar cell is a hetero-

Table II. Selected Parameters of Thin-Film Cells [5].

Cell Material	Semicond. Thickness μm	Cell Area cm^2	Absorber Energy Gap eV	Illumination mW/cm^2	Max. Efficiency %
Si/Si	0.25	9.0	1.1	93	9.5
$\text{Cu}_2\text{S}/\text{CdS}$	0.25	0.9	1.2	88	9.15
CdTe/CdS	0.08	0.1	1.44	70	8.7
$\text{Cu}_2\text{S}/\text{ZnCdS}$	0.25	1.3	1.2	87	8.7
$\text{CuInSe}_2/\text{CdS}$	0.01	1.2	1.04	100	6.6
GaAs/Insulator/Metal	0.25	9.0	1.43	93	6.5
InP CdS	0.25	0.25	2.3	74	5.7
Si/Insulator Metal	0.01	0.02	1.6	65	5.6
$\text{CdSe}/\text{ZnSe}/\text{Au}$	0.02	0.01	1.7	100	5.0
$\text{Cu}_2\text{Te}/\text{CdTe}$	0.10	6.0	1.4	100	4.8
$\text{CuInS}_2/\text{CuInS}_2$	0.04	0.12	1.55	100	3.3
$\text{Zn}_3\text{P}_2/\text{Mg}$	0.10	0.025	1.5	33	3.0
InSe/Bi	0.10	-	1.3	70	1.3
$\text{Cu}_2\text{O}/\text{Cu}$	2.50	1.0	2.0	100	1.1
CdSe/ZnTe	0.10	0.1	1.7	85	0.6
Al/Merocyanine/Ag	0.05	1.0	2.0	-	0.7

junction of Cu_2S and CdS (see Fig. 3). The active region of the cells consists of a 100-300 nm layer of copper sulfide (Cu_2S) formed on a thicker cadmium sulfide (CdS) film which has been grown on an appropriate substrate such as electroformed Cu plated with about 1 μm of zinc (Zn). Light is absorbed in the smaller band gap Cu_2S layer. The light absorption of Cu_2S is well matched to the solar spectrum. Because of the high absorption coefficient, a very thin layer is sufficient to absorb a significant fraction of the incident sunlight.

The cell fabrication procedure is simple. In one process, CdS is evaporated on a thin Cu foil and the Cu_2S layer is formed by dipping into a high temperature cuprous ion solution. The evaporated layers without additional treatment are relatively conducting because of the presence of excess cadmium. The resistivity of these films could be as low as 1 to 10 Ohm. These layers are about 5-10 μm thick. With the present fabrication process, the CdS layer must be thick enough to prevent the Cu_2S from diffusing along the grain boundaries deeply enough to reach the metal substrate and short-circuiting the heterojunction. However, imper-

*** The conversion efficiency of a solar cell is defined as the ratio of electrical power output to solar power input.

fections such as grain boundaries, and low mobilities and lifetimes of the carriers in the Cu_2S , are not critical because this layer (an active one) is thin.

While the Cu_2S must be well protected against oxygen and water vapor, there is no need for an antireflection coating, because the cell surface is rough. A laboratory $\text{Cu}_2\text{S}/\text{CdS}$ cell has produced a conversion efficiency of about 8.6% in sunlight. Figure 3 shows a cross-sectional view of a typical $\text{Cu}_2\text{S}/\text{CdS}$ cell.

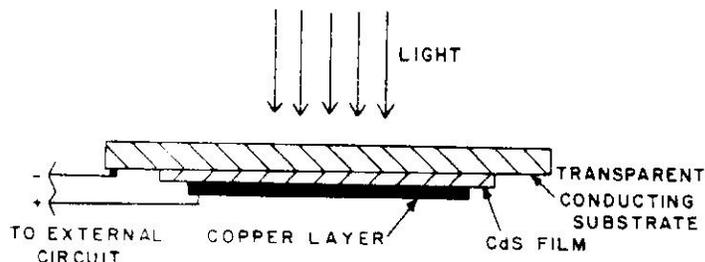


Fig. 3. Cross-Sectional View of $\text{CdS}/\text{Cu}_2\text{S}$ Cell [6].

Solar cells made of cadmium telluride (CdTe), which has energy gaps between 1.2 and 1.4 eV, have attracted attention in recent years because of their maximum theoretical conversion efficiencies of about 26%.

2.3.3. Gallium-Arsenide Cells

Gallium arsenide (GaAs) is emerging as a very promising material for both high-efficiency single-crystal and thin-film solar cells. GaAs possesses the desirable properties of a high absorption of the solar spectrum and acceptable values of the carriers' mobility.

Three different high-efficiency types of GaAs cell structures are currently being developed: GaAs homojunctions with a top "window" layer of GaAlAs , GaAs shallow-homojunctions, and GaAs MIS junctions. Each type is aimed at minimizing the effects of the surface recombination of charge carriers. Such recombination effects are more severe in GaAs than in silicon because of the shallower absorption depth of sunlight in GaAs ; they can severely reduce the photocurrent which reduces the conversion efficiency.

Although gallium is much more expensive than silicon, it is capable of significantly higher efficiency. In addition, it has a much higher tolerance to heat - a major benefit for photovoltaic thermal hybrid systems. The limited natural abundance of gallium will restrict large-scale use of either small concentrator cells or thin films.

The thin layer of GaAlAs transmits almost all the solar spectrum and forms an effective solar "window." Single-crystal cells built in this manner have produced conversion efficiencies as high as 21 to 22%. For comparison, polycrystalline silicon in 24 μm thick layers provided cells with efficiencies of 10%. The tech-

nology based on polycrystalline GaAs cells is still at an early stage. Unfortunately, in thin-film cells the p-dopants in the GaAs layer appear to diffuse down the grain boundaries and short-circuit the junction. Research efforts are being directed at solving this problem.

Thin layers of GaAs (a few tens of microns thick) grown on potentially inexpensive foreign substrates such as tungsten, graphite, molybdenum or glass have the potential for making use of the desirable characteristics of the gallium arsenide while at the same time conserving Ga. However, the development of this technology has been slow; this is reflected in the low efficiencies, which are significantly less than 10% for cells formed from layers grown on foreign substrates. Thin-film polycrystalline GaAs cells of the MIS type (metal-insulator-semiconductor) have been fabricated in this way to yield efficiencies in the range of 6.5%. By comparison, cells of the same type have yielded efficiencies as high as 17% for single crystal GaAs and 14% for polycrystalline GaAs wafers cut from an ingot with crystallite sizes on the order of 100-500 μm .

The efficiencies of the best GaAs cells are already high, but further development should be encouraged with the aim of achieving efficiencies in the range of 25-30% at approximately 50 C and a concentration ratio of 500X.

2.3.4. Amorphous Silicon Cells

Of the classes of thin films ready for pilot production, amorphous silicon devices are the most promising. Amorphous semiconductor solar cells have been fabricated in various device structures: Schottky barriers, metal-insulator-semiconductor (MIS), positive-intrinsic-negative (PIN), and heterojunction. While most earlier research involved Schottky barrier and MIS device structures, the more recent work has been devoted exclusively to PIN and heterojunction structures. PIN cell efficiency up to 8% was obtained for a cell area of 1 cm^2 .

Figure 4 shows the cross section of a typical amorphous silicon solar cell. It consists of

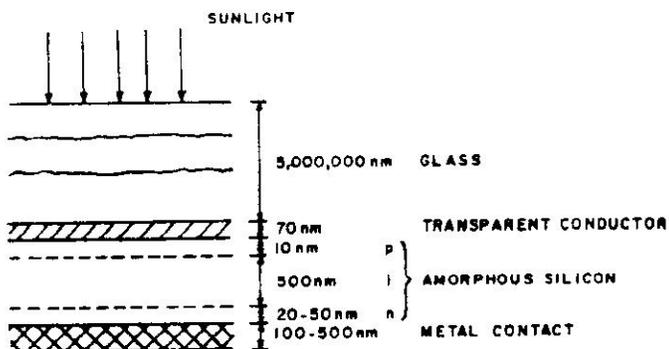


Fig. 4. Cross-Sectional View of PIN Type Amorphous Silicon Cell [7].

three thin layers deposited on a supporting sheet of glass. The first layer is a transparent conductor approximately 70 nm thick. The transparent conducting oxide is either fluorine-doped SnO_2 or InTO (indium-tin oxide). The second is the amorphous silicon photovoltaically-active layer, which typically consists of three sub-layers: (1) a 10 nm thick p-type contact layer; (2) a 500 nm thick intrinsic layer; and (3) a 20-50 nm thick n-type contact layer. The last layer is a 100-500 nm thick back metalization layer of aluminum or another reflective metal or metal combination. Thus the total thickness of the amorphous silicon thin film device is less than 1 μm as compared with a typical crystalline silicon cell of 100-300 μm thickness. Amorphous silicon can be effectively used in such thin layers because it absorbs much more sunlight than its crystalline counterparts.

The highest verified efficiency report for an amorphous silicon solar cell of 1 cm^2 area is less than 3.5%. A comparison of similar solar cells based on two to five micron thick layers of polycrystalline silicon indicates that the polycrystalline silicon will have at least a 25% higher efficiency than the amorphous silicon [8].

For amorphous silicon cells that use platinum Schottky barriers, efficiencies up to 6.1% have been realized for cells of 100 cm^2 area. Fill factor and short circuit currents must still be improved to obtain an efficiency close to the theoretical value of ~15%. Current research concentrates on the elimination of sunlight induced degradation of cells and the fabrication of cells of 12% efficiency (area of 1 cm^2) or 8% (area of 100 cm^2) by glow-discharge deposition [9].

The anticipated low cost of amorphous silicon solar cells will be due mainly to the low silicon requirement and to the low-temperature, large-area, continuous deposition processes. The major material component of the cell is the supporting substrate on which it is fabricated.

During the past decade, a large amount of research has been performed in the United States, Japan, and Europe on hydrogenated amorphous silicon (A-Si:H) materials for solar cells. Hydrogenated amorphous silicon is a glassy semi-conducting material, a disordered alloy of silicon and hydrogen. The hydrogen concentration can be adjusted to produce an energy band gap well-matched to the solar spectrum. The optical absorption coefficient is high. The standard amorphous n-layer consists of hydrogenated amorphous silicon doped with phosphorus and is typically 200 \AA in thickness. The doped layers in a PIN solar cell are mainly responsible for determining the voltage of the device. To complete the solar cell, a layer of metal such as aluminum is deposited on top of the amorphous material to collect the generated current.

The material differs from the more familiar crystalline silicon and polycrystalline silicon in that it also contains hydrogen, and the

material thickness for cells is typically 1 μm instead of the 100-300 μm required for single crystal and polycrystalline silicon solar cells.

Although considerable research has been done on hydrogenated amorphous silicon there are yet not answers to many fundamental problems. A basic difficulty is that the structure of the material and its stability under solar illumination are not sufficiently known. It is also not clear whether these cells' longevity can be made adequate for solar applications.

To increase the efficiency of the amorphous hydrogenated silicon cell, a new type of cell structure has been introduced. The cell consists of three stacked cells, one of standard hydrogenated amorphous silicon while the other two cells use an alloy of silicon, germanium, and hydrogen for the intrinsic (current-generating) layer. This stacked hydrogenated amorphous silicon cell has already reached a conversion efficiency of 8.5% in laboratory conditions, and is referred to as a stacked-junction or cascade cell. The higher efficiency results from capturing a larger percentage of the solar radiation. In this case, the A-Si:H cell captures the blue-green end of the solar spectrum while the A-SiGe:H cell captures more of the red part of the solar spectrum. Theoretical calculations of this three-cell structure with band gaps of 2.0, 1.7, and 1.45 eV give a conversion efficiency of 24% [10]. Figure 5 shows a cross-sectional view of a cascade hydrogenated amorphous silicon cell. The three amorphous silicon layers can be deposited by a number of techniques of which the glow discharge method is presently the leading method of film preparation. Using glow discharge techniques, both doped amorphous silicon as well as mixed alloys can be deposited over very large areas.

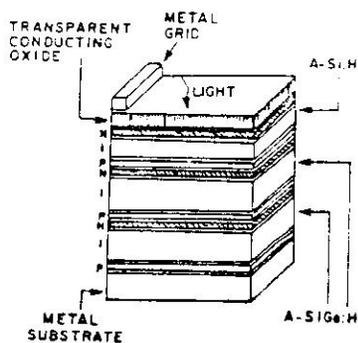


Fig. 5. Cross-Sectional View of Stacked-Junction Hydrogenated Amorphous Silicon Cell [10].

The best amorphous silicon material is made using a glow discharge in a low pressure atmosphere of silane-SiH₄. Under the action of the electric discharge, the silane decomposes and an amorphous hydrogenated alloy of silicon is deposited on a heated substrate. Optimum substrate temperatures range from 140-330°C depending upon other deposition parameters. To form the contact layers it is only necessary

to add small amounts of dopant hydrides to the gaseous atmosphere. For example, the addition of diborane, B₂H₆, forms p-type material typically 50-100Å thick by the incorporation of boron in the silicon, while the addition of phosphine, PH₃, incorporates phosphorus to form n-type amorphous silicon. The "I" layer of the undoped hydrogenated amorphous silicon film is deposited to a thickness of 0.5-1.0 μm . This is the active layer of the cell where sunlight is absorbed and converted to electric current.

Furthermore, by the addition of other elements such as carbon, nitrogen, tin, germanium, or oxygen, new mixed alloys of hydrogenated silicon can be fabricated with different and advantageous optical and electrical properties.

2.4. Innovative Techniques

The main reason for using innovative techniques is to increase cell efficiency and to directly or indirectly decrease cost. Various techniques such as using an inversion layer, a shallow junction, a back surface field, a Schottky barrier or a new cell structure (metal-insulator-semiconductor or MIS; multijunction) have been experimented with.

2.4.1. Inversion Layer Cells

A new cell design which gives high efficiency (currently 17% in laboratory conditions) and high voltage potential was accomplished by using the inversion layer technique. It has been found that a layer of SiO₂ deposited on SiO₂-coated p-type silicon induces a junction near the top of the p-type silicon. Vapor SiO₂ loses electrons as it solidifies, causing the layer of SiO₂ to have a positive charge. This positive charge pulls the few free electrons in the p-type silicon to the interface between the Si and SiO₂, causing that region to behave as if it were n-type silicon; the value of the insulating SiO₂ layer is that it prevents these electrons from entering and neutralizing the SiO₂. Since the layer just beneath the SiO₂ becomes n-type and the bulk silicon is p-type, a p-n junction is induced in the silicon. When the cell is illuminated, the junction separates electrically opposite charge carriers just like a regular p-n junction. The light-generated electrons have enough energy to tunnel through the SiO₂ and preferentially enter the metal contacts.

Advantages of these cells are the relative simplicity of handling SiO and SiO₂; the induced junction within a relatively fault-free material (less doping means fewer lattice defects); and the potential for high voltage and efficiency. This inversion layer or back-contact cell produced also 6-8% higher short-circuit current than a traditional silicon solar cell. By applying antireflective coating the light reflection losses in this cell could be reduced up to 4% with respect to about 5% for other cells and to 36% for untreated silicon. The main advantage of this cell, however, is the elimination of all self-shading because the cell has no front contacts. The disadvantage of this cell is its high cost.

2.4.2. Shallow Junction Cells

Since diffusion lengths usually vary from 10^{-3} to 10^{-2} cm and the charge carriers' generation decreases exponentially from the junction surface, one would desire the junction to be very shallow. Investigations of the influence of junction depth on the photovoltaic cell short-circuit current and the short-wavelength response indicated that the majority of the current gain could be obtained by forming a junction between 0.10 and 0.15 μm in depth, in comparison to 0.35-0.50 μm in traditional cells.

The shallow junction allows the cells to convert more of the short-wavelength portion of the solar spectrum to useful energy. Today all shallow junction cells or "violet" cells use either a quartz cover coated with a 350 nm filter or ceria-doped microsheet.

The disadvantages of a shallow junction are that the series resistance, due to conduction in that thin layer, becomes high; and, the recombination of charge carriers at the surface is much higher than in the bulk material.

2.4.3. Back Surface Field Cells

In order to increase the collection of charge carriers, a field may be introduced at the back surface of the cell to discourage the drift of the wrong carriers toward the back contact. The back surface field (BSF) thus introduced will block the drifting of electrons toward the back contact where they would have been lost due to recombination and repulses them back toward the junction.

The BSF is set up in a cell during its fabrication in much the same way as a p-n junction. For instance, a BSF can be created in a typical cell that has a thin n-type silicon layer atop a thicker base layer of p-doped silicon by doping a thin layer (1 μm) of higher concentration p-dopant (boron) into the back of the cell by raising the silicon temperature in the presence of boron during the fabrication process. This creates a cell having three layers: n on p on p⁺ (the p⁺ indicates the higher concentration of p-type dopant).

A back-surface field can enhance a cell's output voltage by 10% (about an extra 0.05 volts) and raise a cell's efficiency by a few percent. Due to higher voltage output, the fill factor* of a BSF cell is higher with respect to non-BSF cells using identical contact configurations and starting material. This effect is especially pronounced in the case where the bulk resistivity of silicon exceeds 15 Ohm.

Research is being conducted to develop a reliable economic manufacturing process for BSF cells combined with shallow junction technology.

* Typical fill factor for single-crystal silicon cells is 0.72-0.80 while for thin film cells it could vary from 0.25 for a AL/Merocyanin/Ag cell to 0.72 for a polycrystalline silicon cell.

2.4.4. Schottky Barrier Cells

Photovoltaic devices are not limited to charge separation by use of p-n junctions but can use a junction of any two materials which have different electrical properties. One of the types of junctions being investigated for solar cells is the Schottky barrier, which results at the interface of a metal and a semiconductor.

A Schottky barrier is formed when a thin metal (100 Å) is deposited on a surface of n-type silicon. As a result of the electronic properties of silicon and metal, charge carriers are distributed at either side of the contact interface in a way that induces a built-in field just inside the surface of the silicon similar to that of a p-n junction. When light strikes the Schottky barrier cell, the electron-hole pairs are generated in the silicon. Holes then migrate into the metal contact, and electrons from the metal migrate into the silicon (assuming n-type silicon); this causes a current to flow. The advantages of the Schottky cell is that it eliminates the top-surface, oppositely doped collector layer.

Unfortunately, Schottky cells have exhibited much smaller efficiency than p-n junction cells and are prone to degradation, especially in humid climates. Other designs that are being studied include metal-insulator-semiconductor (MIS) and semiconductor-insulator-semiconductor (SIS) cells, which are variations of the Schottky cell.

A metal-silicon oxide-silicon (MIS) structure works better than a regular metal-silicon contact. The insulator is usually very thin (20 Å or less) so as not to impede the passage of current during solar illumination. In a SIS cell the thin transparent layer of metal on the surface of the cell is replaced with a somewhat thicker layer of heavily doped, conductive, transparent semiconductor such as indium tin oxide. This top layer acts just like the metal to induce the junction (in the oxide layer), but has the added advantage that it can be made thick enough to reduce substantially the need for the top-surface electrical contact required in Schottky cells without incurring resistance losses.

MIS and SIS cells have most of the problems of normal Schottky cells, especially quality control during fabrication (because of their thin but very electrically sensitive layers) and degradation during operation. As of now, MIS and SIS cells on single-crystal silicon wafers are not very promising.

2.4.5. MIS Cells

To form a MIS cell, an ultra-thin (30 Å) interfacial layer (so that carriers can tunnel through it) is inserted between a suitable thin (100 Å) metal and a single crystal wafer of p-type silicon. The version suitable for photovoltaic operation is one in which the selected metal has a low work function, such that an inversion layer is created in the semiconductor under the metal, causing minority carrier current to dominate.

For MIS cells that use silicon as the semiconductor, aluminum has been found to be the most suitable metal, and an insulator thickness of the order of 12-15 Å to give best results. The recently obtained results at AM1* on MIS silicon solar cells could be summarized as: $V_{oc} = .615V$, $J_{sc} = 29.3 \text{ mA/cm}^2$, $FF = 0.75$, and conversion efficiency of 10.2% [11]. The factor limiting the efficiency appears to be the short circuit current density which has a theoretical maximum of the order of 44 mA/cm². In general the results may be more promising by using polycrystalline or amorphous silicon in the future.

2.4.6. Multijunction Cells

Multijunction cells supply a possibility for higher conversion efficiency by providing a better match to the solar spectrum. This is done by employing several junctions of different energy gaps to convert different portions of the solar spectrum to electrical energy. Solar cells with different energy gaps are stacked in such a way so that the top cell, the one facing the sun, has the largest energy gap. This cell absorbs all the photons at the band above its energy gap and transmits less energetic photons to the cells below. The next cell down 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, and so on. The options for combining materials of different band gaps to match the solar spectrum are limited by lattice mismatch which must not exceed 1 to 2% among the different semiconductor layers. The optimum thickness for the multilayer cell has been determined to be 10-20 μm.

Breaking up sunlight with multijunction cells and solar spectrum splitting with filter-reflectors are two novel cell approaches that promise to boost conversion efficiency. Photovoltaic conversion efficiencies of 25 to 30% have been reached by dividing the spectrum so that high-energy photons fall on solar cells with high band gaps and lower energy photons fall on solar cells with lower band gaps. A way of packaging the solar cells that makes good electrical contact without blocking off most of the incident sunlight is also being employed.

Spectral splitting is easier to implement than multijunction cells and offers a wider choice of semiconductor combinations. Theoretically, by splitting the solar spectrum into ten different portions and matching these portions with suitable solar cells, 43% of the light can be converted to electricity with respect to up to perhaps 30% at present (depending on the cell). The stacked cell configuration has the advantage of simplicity and compactness. Fabrication may be accomplished by epitaxial deposition of several layers of different semiconductors with corresponding distributions using liquid or vapor phase deposition.

* Air Mass 1 is defined as the power density of sunlight at the depth of atmosphere equal to 1 mile; solar power density equals 930W/m².

An example of a multijunction cell using stacked junction hydrogenated amorphous silicon is shown in Fig. 5.

3. CONCENTRATOR TECHNOLOGY

Concentrator optics vary from 10X-ratio designs such as the 10X concentration of Winston collectors, which do not require elaborate tracking of the sun, to much higher-ratio systems that use parabolic mirrors or Fresnel lenses and which require precise two-axis tracking. The loss of some of the sunlight occurs by the use of a lens or mirror. This loss is often about 15% of the total sunlight, a significant fraction.

Cell temperatures can easily rise to the point where conversion efficiency decreases, rather than increases, from the concentration, and for this reason some concentrator cells must be equipped with cooling systems. Silicon cells perform poorly at high temperatures and are appropriate for concentrations of less than 100X. To be used in concentrating arrays, silicon must be cooled to near-ambient temperatures. For example, the decrease in the conversion efficiency of ordinary silicon cells with increasing temperature is quite large, down from a theoretical maximum of about 22% at 20°C to only 14% at 100°C, while the theoretical maximum efficiency of GaAs cells is still about 20% at 100°C.

In practice, silicon cells have achieved conversion efficiencies as high as 18% at AM1 with a 300X concentration of sunlight and cell temperatures of about 25°C. GaAs cells have attained remarkably high efficiencies of about 24.6% at AM1 with a 180X concentration of sunlight and cell temperatures of 50°C.

Normally, the efficiency of a solar cell is fundamentally limited by the ability of a single semiconductor to use optimally only a small fraction of the broad solar spectrum. Optical filter-reflector systems can be used to split the solar spectrum into several different energy ranges, directing each range upon cells that are optimally designed for that particular range. Figure 6 illustrates the principle of the beam splitting concentrator enhanced cell system.

An especially promising approach is the use of novel concentrators and high efficiency cells such as GaAs-ALGaAs. This high-band gap cell differs only slightly from the normal GaAs solar cell; its p-n junction is formed in a layer of ALGaAs for a band gap of 1.65 eV. The cell consists of: a high-efficiency optical filter that transmits light with energy above 1.6 eV or below 1.1 eV and reflects light with energy between 1.1 and 1.6 eV; a silicon, low band gap cell; an aluminum/gallium/arsenide, high band gap cell. The conversion efficiency of this cell is not very sensitive to temperature. However, since only the narrow band of the spectrum between 1.1 and 1.6 eV is reflected onto the Si cell, most of the absorbed thermal energy is absorb-

ed in the $Al_{0.2}Ga_{0.8}As$ cell as shown in Figure 6 [12]. The maximum achievable conversion efficiency possible with this approach at a 1000X concentration of sunlight is estimated to be about 40% at 50°C.

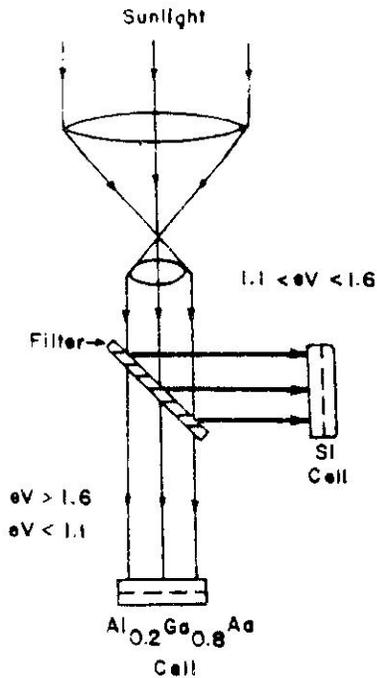


Fig. 6. Schematic of Beam Splitting Concentrator Enhanced Cell System [12].

Another solution being researched is the dye concentrator approach which combines features of both flat panel and concentrator designs. Sunlight (direct or diffuse) incident on a plastic sheet of high refractive index is absorbed by dye molecules in the sheet, or in a film below it, which reradiate light of longer wavelength isotropically. A large fraction of this light is trapped within the plastic by total internal reflection, reducing the losses.

The concentrator enhanced cell development is proceeding toward goal achievement with the development of solar cells and devices for high levels of concentration, highly efficient concentration optical systems, and concentrator-cell arrays.

4. SEMICONDUCTOR/LIQUID JUNCTION CELLS

Semiconductor/liquid junction cells are innovative devices that convert sunlight either directly into electricity, store it in the form of chemical energy, or do both. Such cells have an obvious advantage over solid-state-photovoltaic cells because of their in situ storage capacity. Figure 7 shows a schematic of an electrochemical cell with storage.

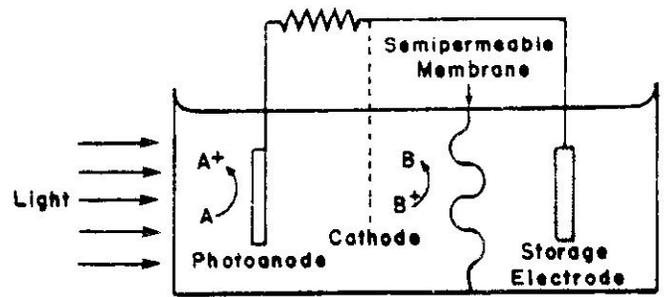


Fig. 7. Schematic of Electrochemical Cell With Storage [10].

In semiconductor/liquid junction or electrochemical cells at least one of the electrodes is a semiconductor. The junction is formed by simple immersion of the semiconductor in the liquid. Such a semiconducting electrode results in an induced flow of current in an external circuit when subjected to sunlight exposure. Such a cell is distinct from a photogalvanic cell, in which light absorption occurs in the solution and not in the electrode.

Electrochemical cells with large-area photoelectrodes (27 cm²) without the storage feature that convert sunlight directly into electricity at an efficiency of 4 to 5% have demonstrated stability for a period of one year under sunlight conditions. To date, the overall conversion efficiency of an electrochemical cell with storage is about 2%.

However, theoretically, like all other semiconductor-based photovoltaic systems, electrochemical cells have an efficiency controlled by the threshold excitation energy, namely, the band gap of the semiconductor.

The stability of the semiconductor photoelectrode against photocorrosion under operating conditions is one of the research problems to be solved. Other problems include encapsulation of the liquid, and the counterelectrode and its positioning. Also, the kinetics of interfacial charge transfer is poorly understood, and has been limiting the potential of semiconductor/liquid junction cells.

5. ECONOMICS

The space market has continued, until the 1970s, to provide the major impetus for the solar cell development, and single crystal silicon cells have continued to dominate and satisfy the space program demand. In part, this is because the solar cell industry has been able to borrow from the technological advances made by the silicon-based microelectronics industry, to increase the efficiency/weight ratio of silicon cells to relatively high levels, and to develop cells of high reliability and durability in the AMO environment. Because of these and other technological advances, the cost of solar cells, since 1973 alone, has dropped one hundred fold, from \$1,000 to less than \$10 per peak Watt by 1980.

The silicon cell cost problem is related to the expensive process used to manufacture silicon. The current process produces silicon at a cost ranging from \$40 to \$75 per kilogram. The outlook for newer, low-cost manufacturing techniques is good. But advance technologies probably won't be ready for commercialization before 1986. One of the technologies in the development stage is the use of a fluidized bed reactor for the pyrolysis of silane. The latest economic analysis shows that the fluidized bed reactor is capable of producing silicon at \$11.65/kg (1980\$) and 10% return on investment cost, utilizing a 1000 Mt/year production plant [13]. The current polycrystalline silicon technology is based on large grain cast ingots and cannot be expected to achieve cell cost much below \$2.00/W_p, while the thin-film approaches are expected ultimately to achieve a cost well below \$0.70/W_p [11].

The photovoltaic system cost requirements vary for different types of applications, so two system-price goals have been adopted: \$1.60 - 2.60/W_p by 1986 for applications such as distributed, grid-connected uses, and \$1.10 - 1.30/W_p for long-term applications such as central power stations [14].

One key assumption underlying the U.S. Photovoltaic Program is that only extensions of presently established technology and its scaling-up to mass production levels are necessary to achieve these goals.

To calculate the cost per kWh of electricity produced by a photovoltaic cell, the following formula can be used [15]:

$$\text{Cost/kWh} = (\text{Cost/W}_p) \times 1000 / (\text{yrs of life} \times \text{hrs of peak sunlight/yr.} + \text{interest cost on outstanding principal})$$

Using 20 year cell life, 12% interest costs, linear amortization of principal, and 2,000 hours of peak sunlight equivalent per year, a photovoltaic array with a cost of \$10 per peak Watt to the purchaser, one will obtain the electricity cost of 55c per kWh.

In the near future, however, major cost reductions are expected with the use of extremely thin semiconducting films on inexpensive glass substrates. Thin-film cells in flat-plate systems will probably be a viable approach if array efficiencies near 10% can be combined with cell costs under \$20 per square meter. High-concentration systems, which involve concentrations greater than 100X, also appear promising if cell conversion efficiencies of about 25-30% can be achieved. However, these systems may require forced cooling, which would be a marked disadvantage in some areas. On the other hand, from the cost reduction point of view, low- and medium- concentration approaches (i.e., 3X - 50X) appear to have little potential in the long run.

The major thrust of the photovoltaic industry is to reduce the cell module price from \$10/Watt to \$1-2/Watt as required by the long term residential/utility market. However, photo-

voltaic cells are already cost-effective today in many applications.

6. APPLICATIONS

Today, photovoltaic systems are capable of transforming one kilowatt of solar energy falling on one square meter into about a hundred watts of electricity. One-hundred watts can power most household appliances: a television, a stereo, an electric typewriter, or a lamp. In fact, standard solar cells covering the sun-facing roof space of a typical home can provide about 8500-kilowatt-hours of electricity annually, which is about the average household's yearly electric consumption. By comparison, a modern, 200-ton capacity electric-arc steel furnace, demands 50,000 kilowatts of electricity and would require about a square kilometer of land for a photovoltaic power supply.

Commercial markets for applications such as cathodic protection of pipelines, wells and bridges - a process in which voltage is applied to prevent their corrosion, radio repeaters, and navigational aids are developing for photovoltaic cells even at the current high prices of \$7 to \$10/W_p [16]. A principal characteristic of all such remote photovoltaic systems is that they operate as "stand-alone" generators with a need of only partial battery storage.

The U.S. Department of Defense is interested in photovoltaic systems for remote communications facilities and for charging the batteries of portable field communication equipment. Another potential market is the cathodic protection of tanks.

Other applications for photovoltaic cells which are beginning to appear are power for educational TV sets in developing countries, lighting for domestic use in rural areas, and power for medical refrigerators and lights in remote medical centers of these countries. One of the largest potential markets is use of photovoltaic cells to power water pumps for domestic or livestock use, and for irrigation systems. This is a particularly appropriate use of photovoltaic cells since, unlike most other applications, electrical storage (batteries) is not required because the water pumped in daylight hours can be stored for use at any time.

It should be recognized, however, that although the achievement of the projected costs for photovoltaic cells may open up new markets for their applications, it is not likely to result in widespread utility uses soon because of inherent problems related to energy storage.

7. CONCLUSIONS

The development of an economically competitive photovoltaic technology is handicapped by the lack of a strong scientific and technological knowledge base.

The performance of currently envisaged photovoltaic cells depends critically on the basic knowledge of the cell materials and an understanding of the physical processes which occur during the energy conversion. Research should continue to identify more suitable materials for cells that will include solids, thin films, and liquid solutions. Once these materials are identified and their structural, chemical, optical and electrical properties characterized, they will have to be mass produced.

Especially new materials with strong optical absorption and band gaps matched to the solar spectrum need to be identified and characterized. Structural research should also address changes in materials produced by intense and/or long solar illumination, high temperature, and exposure to various environments. Research should continue on the reliability and durability of cells and modules that are constructed using improved materials and techniques. A better understanding of the photovoltaic effect when using these new materials and of the parameters governing the efficiency of a variety of cells will benefit the technological development of the photovoltaic field.

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