

The Potential of Photovoltaics

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Abstract

Photovoltaic devices directly convert light to electricity. While the science of such phenomena has been studied since the 1800's, it wasn't until the early 1950's when scientists at Bell Labs made the first photovoltaic devices capable of powering circa electronic devices. These early devices were made from crystalline silicon. Since then many new material systems have been tried with varying degrees of success. The appeal is obvious, a way to make electricity with a free "fuel" supply. In order to compete with existing energy resources, these early solar cells had to be produced at significantly lower cost, have higher conversion efficiency, and be more reliable in order to withstand the outdoor elements for decades of service life. In fact, it is these three considerations that still drive the bulk of the photovoltaic (PV) research and development today. In this paper I will discuss where PV can fit within the context of the world marketed energy portfolio, describe the basic workings of a PV device, detail some of the more common PV technologies, and highlight where vacuum web coating applications exist within those technologies.

Introduction

Energy is critical to the economy of every nation of the world as it enables the production and transportation of necessities—food and water—and other goods and services. In 2005 the world will use more than the 462 Quads of marketed energy¹ (i.e., 462 quadrillion BTUs or the energy equivalent of 1.35E14 kW-hrs or 15.5 terawatt-yr). The world uses mostly energy in the form of consumable fuels, both chemical (petroleum, coal, and natural gas) and nuclear (uranium). It is natural that humankind has exploited these resources as they have a high energy density and are abundant. The use of these fuels has driven a rapidly expanding world economy that has grown not only in prosperity, but also in technological sophistication. This economy is completely dependent on energy to manufacture, deliver, and operate almost every product we enjoy. However, since these fuels were first marketed en masse a century or more ago, the population has grown by approximately a factor of four. Couple this population growth with a growing fraction of the population who have access to marketed energy and the amount of energy humankind uses increases every year; in spite of any gains made in energy efficiency. The early energy providers tapped the easy to access pockets and we're now faced with resources that are harder to reach, cost more to develop, and in many cases are impractical to exploit. From an economic perspective, it is time to look seriously to non-consumable energy resources.

Some of the energy provided in the existing energy portfolio is supplied by renewable energy sources with hydro-electricity providing the vast majority of this comparatively small fraction, followed by wind, biofuels, geothermal, and solar. Looking at the existing portfolio it is easy to come away with the impression that because solar energy is not a very big part of this mix, it doesn't have much potential to be a significant player in the energy market. However, it is important to remember that the sun is actually by far the biggest player in terms of energy resources available to humankind, "raining down" a continuous 120,000 terawatts (TW) of power to the earth's surface, after accounting for the $\sim 1/3$ being reflected away. That's 120,000 trillion watts, making the amount of solar energy hitting the earth in one

hour approximately equal to all the energy used by humankind in one year. One way to understand the magnitude of the solar resource is to think about why it gets cold at night. It's because the earth has rotated away from the sun. It is not uncommon in Colorado for a day to start out with frost on the ground and be room temperature by noon. That's at least a 40°F (22°C) increase in temperature in a few hours. Think about a large building and how much energy it would take to heat that building that much in such a short time. Now extend the walls of the building to the size of an entire continent, and remove the roof!!!

The sun drives most the other renewable energy resources as well. Hydropower requires rain and snow fall from water evaporation and transpiration (22.8% of the solar power falling on the earth). Ocean thermal energy conversion uses the temperature differential between surface water warmed by the sun and cold deep water to drive a turbine and make electricity. Plants and algae require sunlight for photosynthesis before they can be converted to biofuels (14.3% of solar power falls on land masses). Wind can be used to make electricity directly by turning a turbine or indirectly in the form of ocean waves, but the wind itself is driven by the sun (7% of solar energy). This leaves tidal and geothermal energy as the only renewable energy resources that aren't a direct result of solar energy. Tides go up and down due to the gravitational attraction between the oceans and the moon. The heat trapped in the earth itself is due to both leftover heat of formation and radioactive decay of elements within the crust, uranium, thorium, etc. One compelling reason to use PV is to use this vast resource directly.

The consumable energy resources left in the ground worldwide are listed in Table 1. Each of the four big resources—petroleum, coal, natural gas, and uranium—are subdivided into three sub-grades as not all energy resources are of the same quality, not even within each sub-grade. For example, humankind has used about one half of all the crude oil that was in the ground. The remaining half is in smaller pockets that are much more difficult to reach and therefore will cost much more than the first half. Beyond that we must go into very energy intensive and environmentally dirty oil sources. Similarly, the fuel value in the various grades of coal range between the three listed from over 26 to 19 to 9 MBTU/ton respectively. Natural gas is the least well known of the big energy resources. Dry proven is the gas in fields that is relatively dry and has lighter hydrocarbon mixtures, and is therefore the most economical. Wet proven the gas in fields with high moisture and heavier hydrocarbon mixtures requiring more refining. Both those categories are counted by test wells moving quantities from geological estimates into an actual reserves. Unproven is just what it sounds like, geological estimates that haven't been proven by drilling a test well. There are large uncertainties on these numbers.

Table 1: World Consumable Energy Resource Reserves

Resource	Grade (higher to lower)	TW-yrs	Quads	BBoOE	Sun Hrs
Petroleum²	Crude oil	235	7,016	1,210	17.1
	Tar sands	743	22,216	3,830	54.3
	Oil shale	587	17,539	3,024	42.8
Coal¹	Anthracite/Bituminous	461	13,790	3,100	33.7
	Sub-Bituminous	189	5,645	1,269	13.8
	Lignite	49	1,474	331	3.6
Natural Gas³	Dry proven	206	6,157	1,384	15.0
	Wet proven	194	5,799	1,304	14.2
	Unproven	200	5,978	1,344	14.6
Uranium⁴	Current prices	30	885	199	2.2
	1.5x current price	16	475	107	1.2
	Net energy positive	57	1,698	382	4.1

Uranium is the only type of nuclear fuel we currently use in the world, specifically U^{235} which is the minor (0.3%) isotope of uranium that is directly fissionable. Uranium comes in ores of varying grades, those that can produce ore at current prices and those that are more expensive. At some point it takes more energy to get the uranium mined and processed than is gotten back out of using the fissionable product. This doesn't take into account the use of thorium-based reactors or breeder reactors where copious quantities of weapons grade waste is created, thus presupposing moral leadership for centuries.

Various units of energy are provided in Table 1 as a comparison. They are terawatt-years, quadrillion BTUs, billions of barrels of oil equivalent, and the equivalent number of hours of sunlight hitting the earth respectively. If we end up using every last BTU of these consumable energy resources left in the ground, we'll have used the equivalent energy of 217 hours of sunlight hitting the earth, or nine days. Needless to say, this does not take into account the environmental and global warming consequences of extracting these resources, especially the lower grade and more distributed reserves. Economics alone will make the last of these resources unattractive.

Solar Energy

One of the biggest electricity loads is to cool buildings in the summer, because there is too much solar energy. However, the sun can also be used to our benefit in at least four ways. Passive and active solar heating, concentrated solar power and photovoltaics—the later two producing electricity. By carefully designing buildings, sunlight can be let in during the winter and shaded during the summer to passively (nothing being moved with fans or pumps) heat the space. Heat can also be collected in panels and actively moved to spaces via air, water, or heated fluids such as glycol-based solutions. Solar heated water is cost effective for domestic hot water systems and especially so for hot tubs and swimming pools. Concentrated solar power (CSP) technologies use mirrors to convert the energy of the sun into high-temperature heat that is then used to generate electricity in a steam generator. CSP technologies require large array fields—typically in installations exceeding 100 MW—and direct sunlight to focus in order to get very high temperatures. Thus they are not applicable to home applications or locations without good solar resources like those in the southwestern United States. This is in contrast to PV that has applications in much lower solar resource conditions and has installations from a few Watts to multiple MWs. In fact, the largest PV installations in the world are going into Germany that has the solar resource of the northern United States.

While Table 1 shows that the solar resource dwarfs all conventional resource reserves, the solar resource is distributed over a large area, including areas that are remote and inaccessible to humankind for energy production. Roughly two-thirds of the earth is covered by oceans. However, humankind has already covered massive areas of the earth with buildings, structures and roads. In fact, in the last 100+ years humankind has paved more area for roads than would be required to provide all the energy for a world population of 10 billion people at current solar cell efficiencies. If we spend the next 50 years putting PV on buildings, covering rail tracks, along power line easements, and with CSP in otherwise unusable land we could easily change from a fuel-based economy to a solar-electric based economy, and do so in a cost effective way compared to going after the remaining, difficult to obtain, fossil fuels. This is not to say we shouldn't use other renewable resources. CSP and geothermal are more cost effective—in good locations—than PV. Wind is the least expensive way to generate electricity compared to all other technologies provided there is a good wind resource. However, PV is more universal in where it can be sited. We will always need liquid fuels for some applications like air travel, ships, and heavy equipment, but most individual transportation needs can eventually be met with solutions using electricity. There is not enough corn in Illinois to convert to biofuels to move all the people in Illinois. A very rough rule of thumb is that it takes 5 acres/MW for PV and CSP, 50 acres/MW for wind, and 500 acres/MW for biofuels. This makes sense since wind and biofuels are themselves fueled by the sun.

Photovoltaic Basics

Photovoltaic technology is the direct conversion of sunlight to electricity. Photovoltaic can be translated as “light-electricity,” however it is a word that is difficult to pronounce and even more difficult to spell. The first PV devices grown at Bell Laboratories were called solar batteries and the industry may have gotten better public support had that name stuck. The cells work very much like a battery in that there is a positive and a negative terminal, but rather than a chemical reaction producing the voltage and current, light creates an electric field that separates photo-induced carriers to the contacts as illustrated in Figure 1. Historically this has been done with semiconductor materials, primarily silicon. Semiconductors are merely materials with a conductivity between that of a metal and an insulator. In their pure state they are relatively uninteresting because a change in conductivity upon illumination doesn’t produce power. A boundary has to be formed such that a voltage can be produced across that junction. For silicon, a four-fold coordinated atom, substituting a phosphorus atom (with five valence electrons) for a silicon atom in a crystal leaves an extra, unbonded electron that is relatively free to move around the crystal, thus making an n-type semiconductor. Substituting a boron atom (with three valence electrons) for a silicon atom in a crystal leaves a hole (a missing electron) that is relatively free to move around the crystal, thus making a p-type semiconductor. Putting the two materials together makes a p-n junction and due to the two materials having different work functions a potential is built into device. This is the heart of semiconductor devices from diodes to solar cells.

When a p-n junction device is illuminated it creates electron-hole pairs. These charges are free to drift through the semiconductor separated by the internal field, and if connected to an external circuit, can provide power for a variety of applications. An individual cell however doesn’t create much power, on the order of a few Watts. Therefore, cells are assembled into modules—the basic commercial PV product—as illustrated in Figure 2. Modules are then installed in arrays. A given PV system could consist of one to hundreds of arrays and also includes inverters, voltage regulation and may include batteries if the application requires. Typically remote (far from the grid) applications require batteries. Most PV systems are tied to the utility grid and provide power to the utility.

For a building, such a connection is referred to as net metering where solar electricity is sold to the utility when it is produced and bought from the utility when the system isn’t providing enough. Array fields that don’t have a load (e.g., a home or business) are intentionally made for grid power.

This paper focuses on terrestrial PV (used on earth) and doesn’t address space applications where ultra-high efficiency (~40%) gallium-arsenide based cells are used. With the exception of the wafer silicon industry (currently the bulk of the PV industry) vacuum web-coating applications exist in technologies where monolithic integration can be performed. In PV technologies, monolithic integration simply means that all the solar cell components (back contact, semiconductor layers, and front contacts) are manufactured and connected electrically on the same substrate. For thin-film technologies, this means if a module is divided up into individual cells, those cells are interconnected on the same substrate as opposed to wafer technologies where individual wafers are separately tabbed together.

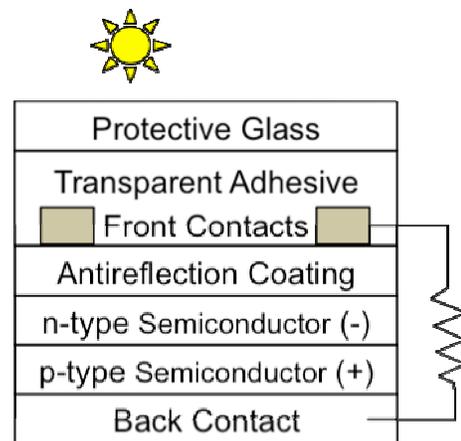


Figure 1: A generic solar cell.

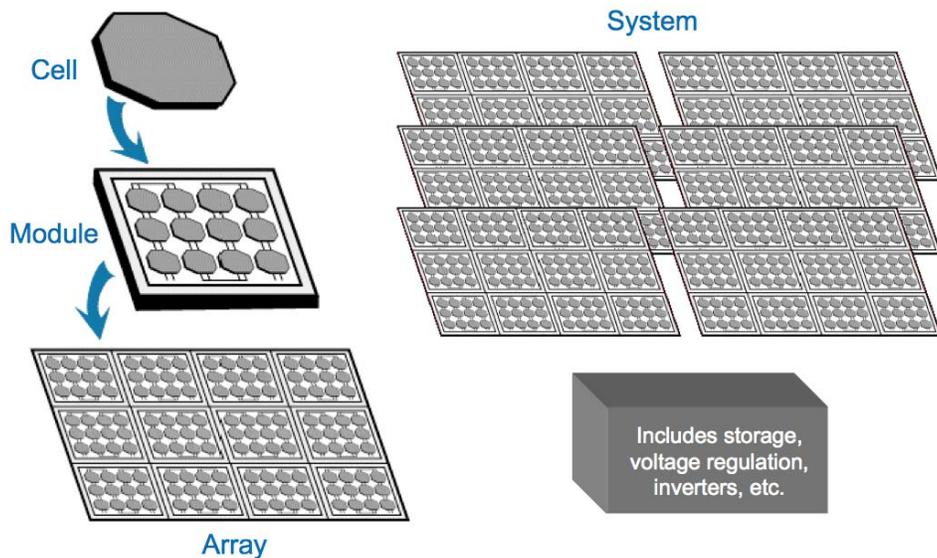


Figure 2: Components of a PV system.

Crystalline Silicon Photovoltaics (c-Si PV)

The vast majority of the PV modules produced are based on crystalline silicon technology, that use silicon wafers. These wafers can be sawed out of a block of bulk silicon—either multicrystalline or single crystal—or grown in thin ribbons that are sectioned into wafers. Typically, wafers are on the order of 200 microns thick. Silicon may be the most well understood element because of integrated the circuit industry. It is also the second most abundant element in the earth’s crust. Because of the size of the existing industry, and the relatively uniformity of sizes and device designs for wafers, there are several companies who provide equipment to the industry thus lowering the barriers to entry for new companies.

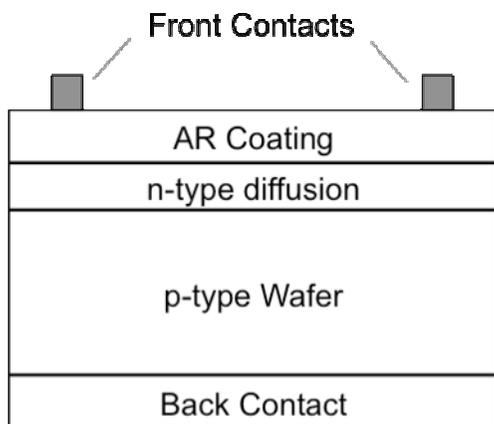


Figure 3: A generic c-Si solar cell, showing an antireflection coating on the top.

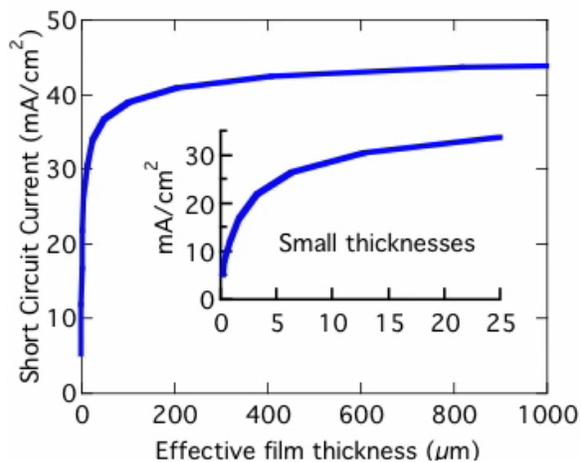


Figure 4: An idealized representation of the current that can be achieved from silicon devices of varying thicknesses.

In spite of all the advantages to crystalline silicon, there is plenty of room for competition. Si wafers are energy intensive to manufacture due to the need to melt silicon that has a melting point of 1410°C. The

current growth rate of the industry is limited by the growth rate of plants that produce high purity silicon. Because silicon is an indirect bandgap semiconductor wafers need to be much thicker than direct bandgap semiconductors to generate the same current. Figure 4 shows the maximum current that can be expected from a silicon cell for a given thickness. The inset represents a smaller thickness scale. Because about half the material is lost in the sawing process, and the wafer is thicker than it needs to be, the material costs alone can account for up to 40% of the cost of a module. Finally, because individual cells are tabbed together individual wafers, monolithic integration is not possible severely limiting web-coating applications.

Hydrogenated Amorphous Silicon Photovoltaics (a-Si:H PV)

Unlike crystalline materials, amorphous materials have no periodic atomic order on any length scale. Amorphous silicon has too many miss-aligned atomic bonds, known as dangling bonds, to be a viable semiconductor. However, when made with a few percent hydrogen (a-Si:H), the hydrogen atoms passivate these dangling bonds and significantly improve the opto-electronic properties of the material. Because the amorphous network isn't a strict 4-fold coordinated lattice a dopant atom can find a location where it doesn't have to be over or under coordinated. There is a high probability that an n-type dopant, like P, can go into the non-crystalline network and bond fully coordinated, and not contribute a carrier (electron) to the lattice. Thus it is perfectly satisfied and doesn't act like a donor which would add energy levels to the conduction band. This is also true for a p-type dopant, like B, which also has a high probability of being incorporated into the bulk fully satisfied and doesn't act like an acceptor which would add energy levels to the valence band. Because of this, it takes orders of magnitude more dopant atoms to dope a-Si:H than it does to dope c-Si. The non-electrically active dopants (which are the majority of the dopant atoms) create more defects and thus deteriorate the opto-electronic properties of the bulk making it unsuitable to make a p-n junction as in c-Si devices. This is why an a-Si:H device is made in a p-i-n configuration where the intrinsic (non-doped, i-layer) layer acts as the absorber, creating the electron-hole pairs which can be separated by the electric field created by the p- and n-layers as illustrated in Figure 5. Light enters these devices through the transparent top contacts.

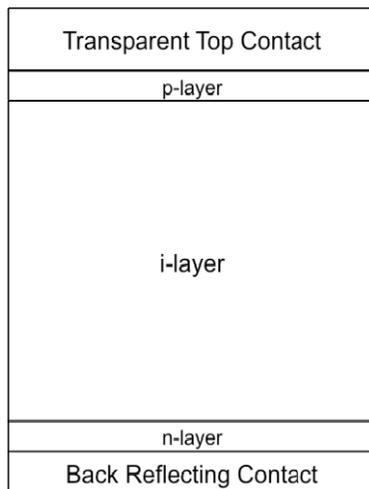


Figure 5: A generic p-i-n a-Si:H solar cell. Superstrate p-i-n devices are grown from top down, while substrate n-i-p are grown from bottom up.

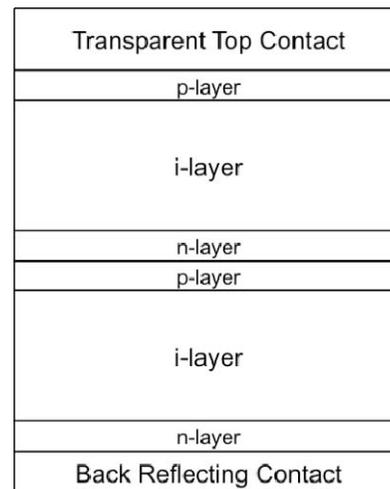


Figure 6: A generic double-stacked a-Si:H solar cell where narrow bandgap materials are used lower in the stack.

The structures can be grown in p-i-n sequence on glass (the opposite direction of illumination, known as a superstrate device) or in n-i-p sequence on glass/metal contact or opaque substrates such as metal foils or plastic rolls (the same direction of illumination and known as a substrate device). The contact layers tend

to be grown by sputtering processes and in manufacturing the Si-containing layers are grown by plasma enhanced chemical vapor deposition.

Because a-Si:H is a direct bandgap semiconductor it can be much thinner than c-Si:H devices. The entire stack of semiconductor layers in Figures 6 and 7 are less than one micron thick. The a-Si:H PV industry enjoys a synergistic relationship with the flat panel display industry with a fairly well understood material system and a history of scientific investigation. There are a few manufacturing advantages to a-Si:H PV including scalable chemical vapor deposition techniques, deposition temperatures below 250°C and the ability to monolithically integrate the process, thus providing many opportunities for web-coating applications. There are a few companies who provide equipment to the a-Si:H PV manufacturing industry thus lowering the barriers to entry for new companies.

In spite of all the advantages to a-Si:H PV, there is plenty of room for competition. An improved hole mobility would improve the solar cell performance. The bandgap is too high to utilize the red part of the solar spectrum. Thus narrower bandgap materials, such as nano-crystalline Si (nc-Si:H) or alloys with germanium (a-SiGe:H) are used in stacked devices. A double-junction device is illustrated in Figure 6 where the top cell is a-Si:H to capture the blue end of the spectrum and the bottom cell is a-SiGe:H to capture the red end of the spectrum. If the bottom cell were nc-Si:H, an indirect bandgap material, it would need to be much thicker on the relative scale of Figures 6 and 7. A triple-junction device is also common with increasing germanium content in the i-layers lower in the stack or thicker i-layers lower in the stack in the nc-Si:H case. Finally, a-Si:H cell performance degrades with illumination (or current injection) and can be restored with annealing. This degradation forces devices to be engineered to maximize stabilized efficiency (agreed upon to exceed 600 hours of 1-sun illumination) rather than initial efficiency. Thinner i-layers, such as those used in multi-junction devices which tend to be about the same total thickness independent of the number of stacks, exhibit less degradation. All these material issues cause a-Si:H to be the lowest efficiency modules of those readily available.

Cadmium Telluride Photovoltaics (CdTe PV)

Between c-Si and a-Si:H—where there are macroscopic grain sizes and no grains whatsoever—are class of materials referred to as polycrystalline thin-films having grain sizes on the order of microns. These materials include CdTe and CuInGaSe₂.

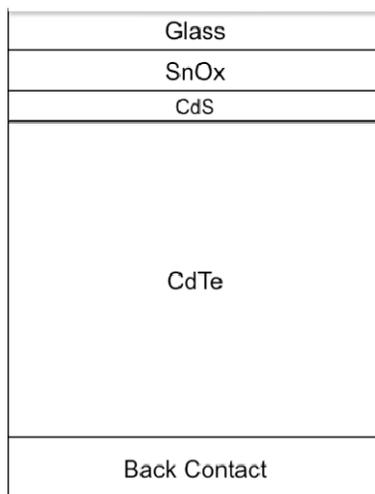


Figure 7: A generic CdTe solar cell structure.

Table 2: CdTe Growth Techniques

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- Top Contacts (SnO₂, Cd₂SnO₄, etc.)
- Sputtering or reactive sputtering
 - Metal Organic Chemical Vapor Deposition (MOCVD)
- Window/Junction Layer (CdS)
- Wet: Chemical Bath Deposition (CBD)
 - Dry: Close Space Sublimation (CSS) or vapor transport (VT) technique, sputtered
- Absorber Layer (CdTe)
- CSS or VT or sputtered
- Back Contacts (SnOx or other material)
- Sputtering or C-paste with Cu or metals
 - Requires a Te rich surface (etch step)

The CdTe solar cell structure is represented in Figure 7 where it is illuminated from the top down, the same as the growth direction, making it a superstrate device. The layers of the device vary from company to company. The CdTe layer tends to be a few microns thick while the other layers are all sub-micron in thickness. Most of the light absorption occurs in the half micron, yet thicker layers tend to produce higher efficiency while thinner layers cost less to manufacture. CdTe has a unique property in that high quality materials can be grown at very high deposition rates using the vapor transport techniques. This makes it attractive to manufacturing in terms of high product throughput. CdTe devices also enjoy a relatively high efficiency for a thin-film device, with record efficiencies in excess of 16%, second only to CIGS. Monolithic cell integration is also possible, coupled with the fact that it is a two-element absorber material, uniformity over a large area is achieved making manufacturing costs some of the lowest of all PV technologies.

In spite of all the advantages to CdTe PV, there is plenty of room for competition. The material itself is not as well understood as Si-based material nor is the device physics or failure mechanisms as well studied as Si-based cells. Individual companies tend to own the intellectual property surrounding the absorber layer growth techniques and thus each company develops their own manufacturing equipment. “Turn-key” CdTe equipment is not available to new start-ups. As is expected to grow materials with crystalline structures the temperature is much higher than for a-Si:H PV and the best materials are grown close to the melting point of glass. Glass is the superstrate of choice limiting web-coating applications. While there is more Cd in a AA battery than in a CdTe module, there is a perception issue with a solar cell containing a toxic heavy metal and the toxicity of CdTe is not well understood. Never the less, First Solar, manufacturers of CdTe modules, is the largest PV producer in the United States shipping 200 MW in 2007.

Copper Indium Gallium Diselenide Photovoltaics (CIGS PV)

The CIGS solar cell structure is represented in Figure 8 where it is illuminated from the top down, the opposite of the growth direction, making it a substrate device. CIGS devices are grown on a variety of substrates, typically glass, but also metal foils or plastic rolls.

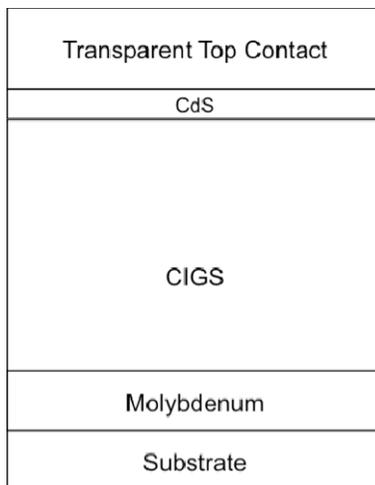


Figure 8: A generic CIGS solar cell structure.

Table 3: CIGS Growth Techniques

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- Top Contacts (ZnO:Al/ZnO, ITO, etc.)
- Sputtering or reactive sputtering
- Window/Junction Layer (CdS typical, can also be ZnO, ZnS, InS, In₂S₃, ZnIn_xSe_y, etc.)
- CBD (for highest efficiency)
 - Sputtered
- Absorber Layer (CuInGaSe₂)
- Co-Evaporation (for highest efficiency)
 - Metal deposition with post selenization
 - Sputtering
 - Screen printing or spray jet
 - Electrodeposition
- Back Contacts (Mo)
- Sputtering

No other PV technology has so many different ways to grow the absorber layer. This is good for new players who may come up with a creative new process and are seeking a competitive funding edge. The method that produces the highest efficiency devices is co-evaporation from the basic elements, however it is difficult to manufacture over large areas. Sputtering of elements or compounds, nano-precursors in suspension for inkjet printing or spraying, and electrodeposition are also used. Sometimes the metallic elements are deposited and the entire bulk is selenized from a gas source with an annealing step.

CIGS produces laboratory cells with the highest conversion efficiency of any thin-film solar cell, close to 20%. The potential of high efficiency has sparked great interest in the technology with dozens of new startup manufacturing companies starting in the last several years. The aesthetics of CIGS modules is often regarded as the best with a very dark and attractive appearance. Because of the thin-film nature of manufacturing monolithic integration is possible, opening possibilities for web coating applications.

In spite of all the advantages to CIGS PV, there is plenty of room for competition. The material itself is not as well understood as Si-based material nor is the device physics or failure mechanisms as well studied as Si-based cells. Individual companies tend to own the intellectual property surrounding the absorber layer growth techniques and thus each there are not any manufacturing standards, however at least three companies in the world have started to sell “turn-key” manufacturing equipment. Because CIGS is a four-element layer it is difficult to get compositional uniformity over large area. This is one of the reasons that manufacturing capacity has lagged behind that of the other thin-film technologies. Like a-Si:H, increasing the deposition rates also decreases material quality, as does lowering the growth temperatures which needs to be high (~600°C). Finally, reliability of flexible products is barrier to enter the building integrated market.

Additional Photovoltaic Technologies

As stated earlier, the three driving goals for PV are higher efficiency, lower cost, and increased reliability. Since none of the previously mentioned flat-plate technologies are a perfect solution for terrestrial power applications there have been many efforts in trying new technologies in order to advance one or more of these goals.

Concentrated PV

Concentrated PV (CPV) uses either reflective optics (mirrors) or refractive optics (lenses) to focus sunlight onto a solar cell. One of the goals of flat-plate collectors is to cover large areas with as inexpensive solar cells as possible. The idea behind CPV is to use large areas of inexpensive optics to focus the light onto high efficiency solar cells. Since the general rule is that high efficiency devices cost more to manufacture than lower efficiency schemes, the cost savings would be in the optics. Until recently high efficiency c-Si cells (~20%) have been used in CPV for terrestrial applications, but very soon ultra-high efficiency space cells (~40%) will surpass c-Si in these systems. These GaAs based, multi-junction devices have a unique feature in that the conversion efficiency goes up with concentration levels to about 300 suns. These systems are inherently systems-oriented in that they require tracking mechanisms to keep the optics pointed directly at the sun. They also require siting in locations with above average solar resource such as in the dessert southwestern United States.

Organic PV

Organic PV (OPV) has organic molecules incorporated into the cell. These molecules can be layers of films and/or incorporate nano-structures. In a conventional semiconductor, light absorption generates an electron and hole which are separated by an internal electric field. In a conducting polymer, an incident photon produces bound electron-hole pairs called excitons which the material “conducts” to an interface

where the exciton dissociates due to the materials having different ionization energies and electron affinities. Recently OPV devices have achieved 5% efficiency. OPV has leveraged on the commercial success of organic light-emitting diodes (OLEDs). OPV is attractive because of the potential for ultra-low cost manufacturing, but this needs to be proven and reliability needs significant enhancement.

Die-Sensitized Solar Cells

Die-Sensitized Solar Cells (DSSC) use a photosensitive dye to coat a high surface area powder (e.g. TiO₂) or nano-wire array (e.g., ZnO). A photoexcited state is created in the dye from which an electron can be injected into the conduction band of the material the dye coats. This electron then diffuses to the anode. Since the dye molecule has lost an electron, it strips an electron from an electrolyte solution. An oxidation-reduction reaction occurs between the dye and the cathode (counter electrode) to complete charge balance and provide current to an external circuit. Laboratory cells (Grätzel) have exceeded 11% efficiencies with modules approaching 7%. The goal is ultra-low cost due to simplified manufacturing. Reliability of DSSC technologies needs improvement prior to widespread power generation.

Summary

Every PV technology has improved in terms of reduced cost, increased efficiency, and increased reliability through the years. The worldwide PV industry has exceeded a 35% growth rate in module production for a decade, more than doubling module shipments every two years. Thin-film technologies, which have many more web-coating applications than wafer technologies, are a minor, but growing, component of the PV worldwide portfolio. In the United States, the majority of the production is thin-films (65%). Commercially available modules are always lower efficiency than the world record laboratory cells, typically ranging between 50 and 70% of the champion device efficiencies. As progress is made in manufacturing, and conventional fuel costs for generating electricity increase, the sky is literally the limit for PV technologies. Humankind's thirst for energy is almost limitless and it is possible for PV to play a major part in the energy mix. See Reference 5 for more PV details. The US Department of Energy has published technology road maps for each of the major PV technologies and they can be downloaded from Reference 6.

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Tar sands and oil shale from Exxon Mobile ad in a Winter 2004/2005 National Review.
- ³ Dry proven is taken from reference ¹, the wet proven and unproven are taken from ratios of US gas reserves applied to the global (uncertain) reserves based on Excel File [ng_enr_sum_dcu_nus_a.xls](#), from U.S. Department of Energy, Energy Information Administration and <http://www.naturalgas.org/overview/resources.asp>.
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<http://www.inb.gov.br/english/reservasMundiais.asp>
<http://www.oprit.rug.nl/deenen/>
All using the current consumption of 64,600 tons/year producing 0.298 TW electricity (2006) as a conversion.
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