



# The Potential of Photovoltaics

## Preprint

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# The Potential of Photovoltaics

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## Abstract

Photovoltaic (PV) 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 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 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 worldwide use of marketed energy was 462 Quads<sup>1</sup> (i.e., 462 quadrillion BTUs or the energy equivalent of 1.35E14 kW-hrs or 15.5 terawatt-yrs) and this number increases every year. This energy consumption is mostly 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 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 that has 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 supplies 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, the time for non-consumable energy sources is here.

Worldwide, 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 by far the biggest potential of energy resources available to humankind, "shining 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 120,000 trillion watts makes 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 of the other renewable energy resources, a compelling reason to directly use solar energy. Hydropower requires rain and snow fall from water evaporation and transpiration (processes that use 22.8% of the solar resource). 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 marketable bioenergy (processes that use 14.3% of the solar resource). Wind can be used to make electricity both directly by turning a turbine or indirectly in the form of ocean waves, but the wind itself is driven by the sun (processes that use 7% of the solar resource). 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 the earth's formation and radioactive decay of elements within the crust, such as uranium, thorium, etc.

The consumable energy resources remaining 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 in column 2 as not all energy resources are of the same quality. This is true 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 such as tar sands and oil shale. Similarly, the fuel value in the various grades of coal range between the three listed in column 2 and were assigned a value of 26, 19, and 9 MBTU/ton, respectively, to get the values in the next three columns. The natural gas may be the least certain 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 is 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 actual reserve counts. Unproven is just what it sounds like, geological estimates that haven't been verified 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
<b>Petroleum<sup>2</sup></b>	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
<b>Coal<sup>1</sup></b>	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
<b>Natural Gas<sup>3</sup></b>	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
<b>Uranium<sup>4</sup></b>	Ores at current prices	30	885	199	2.2
	Ores at 1.5x current price	16	475	107	1.2
	Ores w/ positive net energy	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 mine the uranium and process it into fuel than is returned using the fissionable product to make electricity (an estimate is provided in the final row of Table 1). The use of thorium-based reactors, breeder reactors, and fusion reactors are not included in this paper, as they currently do not provide energy to the market.

Various units of energy are provided in Table 1 as a comparison. They are terawatt-years, quadrillion BTUs, and billions of barrels of oil equivalent. In the final column, is the equivalent energy of sunlight hitting the surface of the earth, in units of hours. If we end up using every last BTU of these consumable energy resources remaining in the ground, we'll have used the equivalent energy of 217 hours of sunlight hitting the earth, or a mere nine days. While the environmental and global warming consequences of extracting these consumable resources—especially the lower grade and more distributed reserves—may be disastrous, economics alone will make the last of these resources unattractive.

## Solar Energy

Solar energy can be used to our benefit in at least four ways; passive and active solar heating, concentrated solar power (CSP), and PV—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. CSP technologies typically 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, which has a similar solar resource to that of the northern United States.

While Table 1 shows that the solar resource available will far exceed all conventional resource put together, the solar resource is distributed over a large area, including areas that are remote and inaccessible for energy production. For example, roughly two-thirds of the earth is covered by oceans and therefore not readily available for solar power generation. 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 per capita energy use and 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, but 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 and biofuels should play an important role for those applications. Eventually, land utilization does become a concern and solar requires much less land per MWhr of energy output than wind, which requires much less land than growing biomass (sans algae).

## Photovoltaic Basics

PV technologies directly convert 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, contributing to public misunderstanding technology. 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, a built-in electric field provides the positive and negative terminals, as illustrated in Figure 1. Typically the active layers are semiconductor materials, primarily silicon. Semiconductors are merely materials with conductivities 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 (P, 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 leaving the bulk with a net negative charge and is called an n-type semiconductor. Substituting a boron atom (B, 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 leaving the bulk with a net positive charge and is called 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 the device. This is the heart of semiconductor devices from diodes to transistors 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 single cell however doesn’t create much power, only 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 possibly batteries, if the application requires. Remote applications (far from the grid) typically require batteries.

Currently, most PV systems are tied to the electrical grid and provide power to the utility.

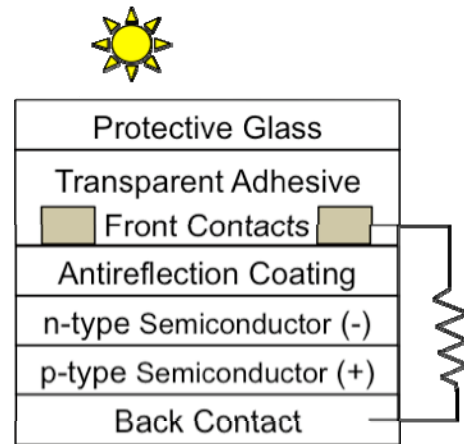


Figure 1: A generic solar cell.

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-arsinide-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 separate but tabbed together.

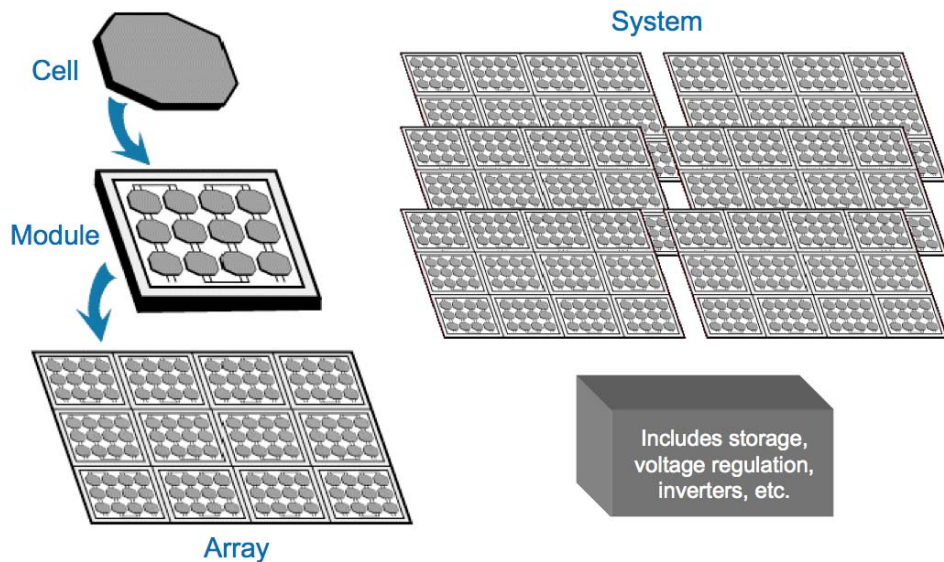


Figure 2: Components of a PV system.

### Crystalline Silicon Photovoltaics (c-Si PV)

The vast majority of the PV modules produced are based on crystalline silicon technology, using 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 (Figure 3). Silicon may be the most well understood element because of the integrated 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 relative 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.

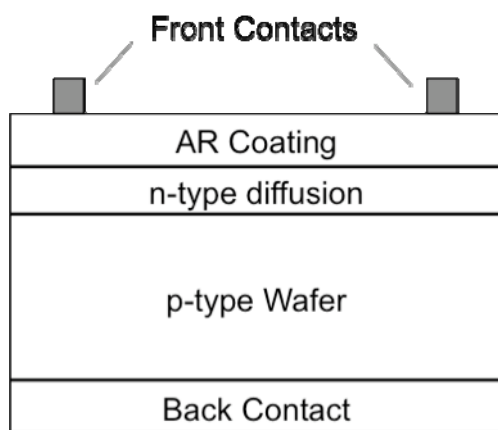


Figure 3: A generic c-Si solar cell, showing an antireflection coating on the top. Wafer thicknesses are typically ~ 200 microns.

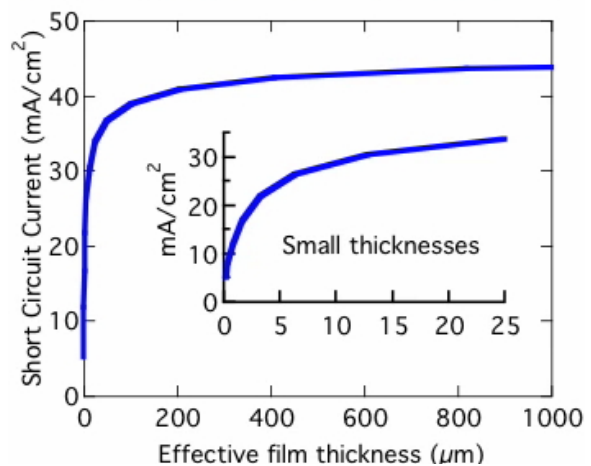


Figure 4: An idealized representation of the current that can be achieved from silicon devices of varying thicknesses.

In spite of all the advantages of crystalline silicon, there is plenty of room for competition. Silicon 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, to generate the same current, wafers need to be much thicker than direct bandgap semiconductors. 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. Since 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, monolithic integration is not possible, thus 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. It is thus 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.

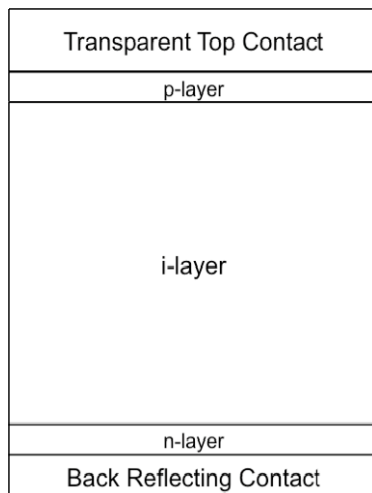


Figure 5: A generic p-i-n a-Si:H solar cell. Superstrate p-i-n devices are grown from top down, while substrate n-i-p are grown from bottom up.

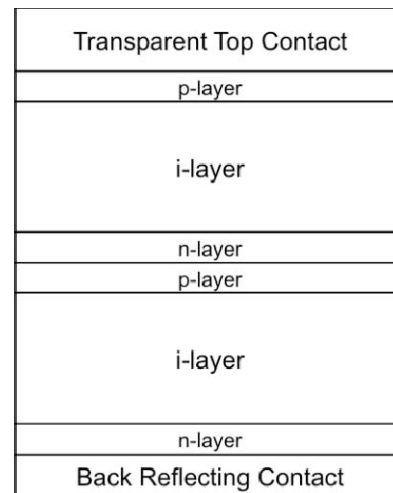


Figure 6: A generic double-stacked a-Si:H solar cell where narrow bandgap materials are used lower in the stack.

The structures can be grown in p-i-n sequence on glass (the opposite direction of illumination and known as a superstrate device) or in n-i-p sequence on glass/metal-contacts 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 silicon-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 5 and 6 are less than one micron thick. The a-Si:H PV industry enjoys a synergistic relationship with the flat panel display industry, due to a fairly well understood material system and a history of scientific investigation. There some manufacturing advantages to a-Si:H PV over c-Si technologies, including scalable chemical vapor deposition techniques, deposition temperatures below 250°C, and the ability to monolithically integrate the layers, thus providing many for web-coating opportunities. As with c-Si, there are enough companies who provide equipment to the a-Si:H PV manufacturing industry that the barriers to entry for new companies are lowered.

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 silicon (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 than what is represented in Figure 6. A triple-junction device is also common, either with increasing germanium content in the i-layers lower in the stack or with 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), yet can be restored with annealing. This degradation forces devices to be engineered to maximize stabilized efficiency (measured after illumination for at least 600 hours at 1-sun equivalent) rather than initial efficiency. Thinner i-layers exhibit less degradation, thus multi-junction devices tend to be more stable because the devices are about the same total thickness, having a larger number of thinner layers. Modules of a-Si:H are the lowest efficiency of those readily available.

### Cadmium Telluride Photovoltaics (CdTe PV)

Between the structures of c-Si (macroscopic grain sizes) and a-Si:H (no grains whatsoever) are a class of materials referred to as polycrystalline thin-films, which have grain sizes on the order of microns. These materials include CdTe and CuInGaSe<sub>2</sub>.

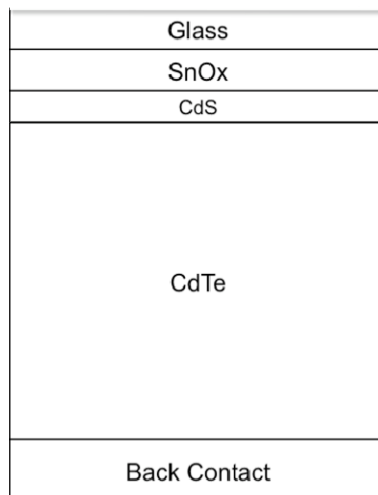


Figure 7: A generic CdTe solar cell structure.

**Table 2:** CdTe Growth Techniques

- 
- Top Contacts (SnO<sub>2</sub>, Cd<sub>2</sub>SnO<sub>4</sub>, 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 are described in Table 2 and 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 of the CdTe layer, yet thicker layers tend to produce higher efficiency devices. CdTe has a unique property in that high quality materials can be grown at very high deposition rates using the vapor transport techniques. (In most materials, properties degrade with increasing deposition rate.) This makes it a potentially high throughput product. CdTe devices also enjoy a relatively high efficiency for a thin-film device, with record efficiencies in excess of 16%. Monolithic cell integration is also possible, and 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 are 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. It takes more energy to grow materials with crystalline structures, thus the CdTe growth temperature is much higher than for a-Si:H PV, with the best materials grown at temperatures 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 module containing a toxic heavy metal and the toxicity of CdTe is not well understood. Nevertheless, First Solar, Inc.—manufacturers of CdTe modules—is the largest PV producer in the United States, shipping approximately 200 MW in 2007.

### Copper Indium Gallium Diselenide Photovoltaics (CIGS PV)

The CuInGaSe<sub>2</sub> 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 with monolithic integration, thus opening possibilities for web coating applications.

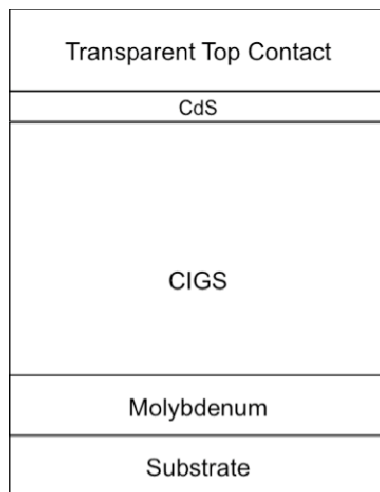


Figure 8: A generic CIGS solar cell structure.

**Table 3: CIGS Growth Techniques**

- 
- Top Contacts (ZnO:Al/ZnO, ITO, etc.)
- Sputtering or reactive sputtering
- Window/Junction Layer (CdS typical, can also be ZnO, ZnS, InS, In<sub>2</sub>S<sub>3</sub>, ZnIn<sub>x</sub>Se<sub>y</sub>, etc.)
- CBD (for highest efficiency)
  - Sputtered
- Absorber Layer (CuInGaSe<sub>2</sub>)
- 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 offers so many different ways to grow the absorber layer (Table 3). 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 involves co-evaporation of 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 to make the CIGS layer. 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 being established in the last several years. Having a very dark and attractive appearance, the aesthetics of CIGS modules is often regarded as the most appealing.

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 are 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 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 a 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 a 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 attempts at developing new technologies in order to advance one or more of these goals.

#### Concentrated PV (CPV)

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 solar cells that are as inexpensive as possible. The idea behind CPV is to use large areas of inexpensive optics to focus the light onto high efficiency solar cells. Since it is a general rule 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 gallium-arsinide-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 locations with above average solar resource, such as in the desert southwestern United States.

#### Organic PV (OPV)

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 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 (DSSC)

DSSC use a photosensitive dye to coat powders (e.g. TiO<sub>2</sub>) or nano-wire arrays (e.g., ZnO) or other large surface area particles. 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 (i.e., Grätzel cells) 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**

Through the years, every PV technology has improved in terms of reduced cost, increased efficiency, and increased reliability. 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. There is enough room at the "energy trough" for all the PV technologies. See Reference 5 for more details on PV. The US Department of Energy has published technology road maps for each of the major PV technologies that can be downloaded from Reference 6.

### **References**

- <sup>1</sup> U.S. Department of Energy, "International Energy Outlook," DOE/EIA-0484(2008)
- <sup>2</sup> Crude oil from U.S. Department of Energy, "World Proved Reserves of Oil and Natural Gas," Table Posted: August 27, 2008, [www.eia.doe.gov/emeu/international/reserves](http://www.eia.doe.gov/emeu/international/reserves)  
Tar sands and oil shale from Exxon Mobile ad in a Winter 2004/2005 National Review.
- <sup>3</sup> Dry proven is taken from reference <sup>1</sup>, 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>  
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All using the current consumption of 64,600 tons/year producing 0.298 TW electricity (2006) as a conversion.
- <sup>5</sup> Antonio Luque and Steven Hegedus editors, "Handbook of photovoltaic science and engineering" Published by John Wiley and Sons, 2003, ISBN 0471491969, 9780471491965
- <sup>6</sup> [http://www1.eere.energy.gov/solar/solar\\_america/planning.html](http://www1.eere.energy.gov/solar/solar_america/planning.html)

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<b>14. ABSTRACT (Maximum 200 Words)</b> This paper summarizes where photovoltaics (PV) can fit within the context of the world's energy portfolio, describes the basic workings of a PV device, details the more common PV technologies, and highlights where vacuum web-coating applications exist within those technologies. 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 production is thin films. 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. Our thirst for energy is almost limitless and PV can to play a major part in the energy mix.					
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