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What is Happening with Regards to Thin-Film Photovoltaics?

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1. Introduction

The advances and promises of thin-film photovoltaics (PV) are much discussed these days, typically using the viewpoint that a picked technology and process approach would provide "the" solution to many problems experienced implementing PV commercialization. In 2009, a thin-film PV company, First Solar, garnered world-leadership as a PV company, being the first company to produce or ship more than 1 GW of PV modules in a single year. This makes it timely to discuss the advantages and limitations of thin-film PV technology, as compared to the currently prevailing crystalline Si PV industry. Traditionally, the following technologies are considered constituting "thin-film PV:"

1. CdTe PV
2. CIGS PV (or copper-indium-gallium diselenide)
3. a-Si:H (and nc-Si:H nanocrystalline or "micromorph" silicon films)
4. less than 50 micron thick crystalline Si films

In the amorphous silicon (a-Si:H) based category, several approaches are pursued, ranging from amorphous silicon single junction modules to spectrum splitting multijunction cell structures using either a-SiGe:H cell absorbers or a-Si:H/nc-Si:H multijunctions. Pros and cons will be given for these different approaches that lead to this multitude of device structures. It is argued that as long as the advantages of the aforementioned materials are not understood, it would be difficult to "design" materials for more efficient solar cell operation.

This review will recap what is currently known about these materials and solar cell devices, keeping in mind that there will always be some unexpected "surprises," while there were many other approaches that did not result in anticipated cell/module performance improvements. This knowledge leads the author to ask the following question: "Was improper implementation or inadequate process choice responsible for the lack of solar cell/module performance improvement, or was the expectation for improved device performance or decreased device cost simply not warranted?"

The chapter of this book is written such as to not prejudge an outcome, i.e., an a priori assumption that a given measure would result in a commensurate expected performance improvement. The impact (i) of an improvement is broken down into probability (p) of achieving a projected improvement times the effectiveness (e) of such improvement, where

$$i=p*e$$

It is of interest to note that while impact is costed and/or priced by many companies, the right hand side of the above equation also has associated cost elements associated with effectiveness e plus an estimated probability p. Probabilities (p between 0 and 1 or 0% and 100%) are often assumed to be either 0% (for an unsuccessful project) or 100% (for a successful project), with the benefit of hindsight. This is true only with the benefit of hindsight, forward looking probabilities should be estimated and accounted for as accurately as possible. In financial terms, a probability between 0 and 1 should be accounted for by applying appropriate financial discounts to probabilities falling outside the extreme values, 0 or 1. Instead, often p=1 is being "assumed," but strictly speaking, this is inadmissible in forward-looking situations. Whenever p is increased at the expense of e, the total benefit for i may not be achieved as planned. Typically, p has to be empirically assessed, which is important for appropriate financial "discounting" leaving much room for discussion as to what value (between 0% and 100%) to assign to p. The foregoing statement is valid for all PV technologies (not just thin-film PV), but in the following, mainly elucidated picking thin-film PV examples. This chapter does not want to chime in on a debate about what appropriate probabilities or discount factors should be used, but rather serve as a reminder to the fact that projected probabilities occur with less than 100% probability.

2. Status and challenges for CdTe based solar cells and modules

In the year 2009, a company relying on producing CdTe based PV modules, First Solar Inc., became the World's largest photovoltaic (PV) company, producing about 1,100 MW of PV modules. Its production costs per Watt were quite low by industry standards. In 2010, direct manufacturing costs of less than \$0.8/W were reported by First Solar. First Solar modules are 120 cm x 60 cm in size and were reported in 2010 to generate between 70 and 82.5 Watts under standard testing conditions, resulting in commercial module efficiency levels on the order of 10% to 11.5%. Time will tell how much room there is to further enhance power ratings and commercial module efficiency. It can be expected that in the foreseeable future, First Solar will remain among the top World Producers of PV modules. The CdTe device is a true thin-film device consisting of a TCO-coated (typically, SnO_2) glass superstrate, a CdS junction partner layer, an active CdTe layer, an often proprietary back contact, packaged in a hermetically sealed package. First Solar buys SnO_2-coated superstrates, uses vapor transport deposition (VTD) for the CdS and CdTe layers, and applies a proprietary back contact and cell series interconnect to the device structure.

Champion CdTe cells have achieved in excess of 16% efficiency (Green et al, 2011). It is of concern to some researchers that this champion cell was reported already some 10 years ago and has not improved since. The compound semiconductor CdTe has a tendency to grow and sublime stoichiometrically when exposed to high temperature. Instead of using vapor transport deposition used by First Solar, many R&D efforts use "Close-Space Sublimation" (or CSS) to deposit the CdTe layer. It appears that the deposition method for the CdS junction partner layer is not of as great importance as in the case of CIGS solar cells, where frequently chemical wet deposition schemes are used for depositing the CdS layer which is only about 100 nm thick, because that deposition method produces the greatest and most reproducible performance. CdTe layers deposited at the highest temperature compatible with the soda-lime glass superstrates typically result in the greatest device efficiency. However, other CdTe deposition schemes, most notably electro-deposition, also resulted in PV modules exhibiting substantial efficiency and performance (Cunningham et al, 2002). It

was, however, found that a critical $CdCl_2$-anneal step is crucial to achieve best solar cell or module performance (McCandless, 2001). Anneal temperatures on the order of 400 °C are typically used after the $CdCl_2$ exposure. For industrial production rates, it is important to limit the time for such anneal step in order to achieve an appropriate throughput. Looking at current commercial throughput rates, one has to conclude that this is possible. It was also attempted to substitute this $CdCl_2$ anneal step (where $CdCl_2$ is often applied as an aqueous solution] with a gaseous anneal step using HCl dry gas (McCandless, 2001). While this approach resulted in similar results as the aqueous $CdCl_2$ anneal step, a superiority using this "dry" process could not be established .

CdTe cells can be made stable and lasting, but not all production schemes result in stable cells. It was reported that excessive reliance on the $CdCl_2$-anneal step to obtain the highest cell or module efficiencies often led to less stable devices (Enzenroth et al., 2005), with processes leading to the highest pre-anneal efficiency often resulted in the most stable manufacturing recipes. It is now known that Cu, applied to many back-contacting schemes, is correlated with the stability of CdTe cells. While it has been established that "too much" Cu results in unstable cells, some rather stable cell deposition schemes were developed that use Cu-doped back contact recipes. The degradation process shows a mixture of diffusive and electromigration behavior (Townsend et al., 2001). Alternatives to using Cu for the back contact were developed (e.g., P-doping, N-doping) (Dobson et al. 2000). These 'Cu-free' recipes also showed instabilities and did so far not improve cell performance over that achieved with stable Cu-containing back-contact recipes. Perhaps, it is a flaw to ask: "Is Cu in the back contact good or bad for cell stability?" The appropriate question may well be: "When is Cu good, when is it bad, and when is it irrelevant for cell performance and stability?"

While all commercial CdTe solar modules are currently fabricated in a superstrate configuration (using a glass superstrate), the question has been posed whether such process could be inverted and/or be applied to flexible substrates. Flexible substrates (like polyimide foil) limit the temperature that can be applied during the position process. Also, the issue of low-cost hermetic packaging of such transparent foils has to be addressed in greater detail in a cost-effective manner. Because glass-encapsulated PV works, the cost of glass (on the order of $10/m² for a single sheet) can often be used as a cost-guideline for terrestrial flexible packaging schemes for power modules. It is clear at this juncture that CdTe PV and CIGS PV have greater moisture sensitivity than many Si PV schemes, requiring a more hermetic seal than Si PV might require. A point of research continues to be the "edge delete" for modules. Typically, SnO_2 coated superstrates are coated with all layers of the entire glass surface. A fast removal of such films, including the SnO_2-layer, along the module edges is required. For CdTe modules, often rather crude methods (like bead-blasting or using grinding wheels) are employed for this "edge delete" step were employed. The drawback of employing these methods is that glass surfaces are damaged using such processes, resulting in greater water penetration rates from the module edges. Also, such processes tend to weaken the glass. However, less damaging edge delete techniques like laser ablation methods are rapidly becoming feasible and more cost effective.

In order to make a monolithically interconnected module, cell "strips" have to be created that carry CdTe currents through the SnO_2. Typically, 1 cm-wide cell strips are used for CdTe modules. These strips require 3 scribes sometimes labeled P1 (SnO_2), P2 (semiconductor layer), and P3 (back-contact) scribe line. The area including and between scribes P1 and P3 is electrically "dead" and does not contribute to module power, hence reducing the total area module efficiency. Therefore, scribe lines should be narrow and close

to each other, which requires a good parallel alignment of the scribe lines with each other. With the advancement of laser technology, all of these scribes are often achieved by laser scribing. CdTe (and CIGS) cells can also be scribed with a mechanical stylus, and sometimes, lift-off techniques were used for the P3 scribe by printing a lift-off paste to segment the cell's back contact. CdTe modules can be scribed in a picture frame or landscape format. First Solar scribes in a picture frame format, arguing that high module voltages would reduce resistive (I^2R) losses in the dc module wiring. However, it was also discovered that modules are installed with a maximum string voltage of 600V (dc, in North America, 1000V in Europe), leading to relatively short strings for high-voltage modules. Realizing this, for its series 3 modules, First Solar has reduced the voltage, resulting in lower voltage (and greater current) PV modules. Other CdTe companies have elected to scribe in a landscape format.

Research activities for CdTe cells and processes concern themselves with achieving a greater open-circuit voltage (V_{OC}), greater stability, and more repeatable solar cell processing. While the CdTe semiconductor possess nearly the ideal band gap for absorbing the solar spectrum in a single junction device (about 1.5 eV), V_{OC} is limited to approximately less than 900 mV for champion cells,(about 750 - 800 mV per cell for commercial devices), well below values that were achieved for high efficiency GaAs solar cells (V_{OC} of about 1200mV in "champion" cells) where the semiconductor absorber has a very similar band gap near 1.5eV. Investigation of back contacts and device stability is sometimes hampered by the proprietary nature used by industry for these processes. Also, the role of impurities (oxygen, water vapor) and the process when and how these impurities are added are currently poorly understood.

Long-term concerns for CdTe PV are a perceived toxicity (Cd-containing compounds) and the availability of Te. While Te availability is not a problem now, it may become so after multiple terra-Watts of CdTe PV have been produced. A known mitigation scheme for incorporating less Te (and Cd) into a cell would be to make the absorber layer thinner. Unfortunately, as the absorber thickness is reduced to values below 1.5 microns, an often precipitous decrease in cell fill factor and V_{OC} were observed. For some solar cell processes, a more gradual decrease of these cell parameters is observed even as thicker absorber layers are thinned. Because absorber material costs are not a significant manufacturing cost factor, manufacturers are reluctant to sacrifice performance by making thinner absorbers, hence the development of thin absorber cells is currently only infrequently pursued. There comes a point when very thin absorber cells would also loose current density due to incomplete light absorption, but in a direct band gap thin-film semiconductor this would only happen for absorber thicknesses below 1 micrometer. Further, as the a-Si:H and nc-Si:H PV communities have shown, it may be possible to mitigate such current loss by employing optical enhancement techniques (Platz et al. 1997).

3. Status and challenges for CIGS based devices

Champion CIGS Cells have been reported near 20% cell efficiency (Green et al, 2011). It is remarkable that (a) 2 different groups on two continents (National Renewable Energy Laboratory, NREL and Center for Solar Hydrogen, ZSW) have achieved this efficiency level, and that (b) different material compositions all can achieve high efficiency cells (Noufi 2010). The record cells were mostly made by a process call co-evaporation. Typically, this process has multiple "stages" involved, finishing devices with a Cu-poor (or In-rich) surface

layer (Gabor et al. 1994). This process has also been adopted for CIGS module manufacturing. Other processes used for commercial module fabrication are sputtering and (time-consuming!) selenization using H_2Se gas, various hybrid processes, electro-deposition, and nano-particle precursor inks. Only time will tell if the latter deposition processes can achieve the same performance as the co-evaporation process can? There are currently different schools of thought as to why best solar cell results are obtained using these multi-stage processes. Some people argue that the Cu-poor surface phase is a perfect ordered vacancy compound (Schmid et al. 1993), while other researchers believe that a non-perfect Cu-deficient surface layer can enhance CIGS solar cell performance (It may be instructive to compare this issue to the crystalline Si PV case. Traditionally, this PV technology has used monocrystalline and multicrystalline Si wafers. While several promoters have some understanding that there is an efficiency difference between mono-Si and multi-Si based technologies, some Si advocates say that all Si cells "should" have the same efficiency potential.)

Nano-particle approaches have been promoted based of the promise that the absorber properties could be fixed in the ink precursor. Nevertheless, the scale-up of nano-particle precursor deposition approaches has also shown significant variation in output power. Researchers typically have the uniformity of a semiconductor absorber layer in mind when looking at enhanced control scheme, thereby neglecting the "junction-uniformity" upon scale up, which can be observed in any commercial manufacturing process even when the absorber properties remain constant upon deposition area scale-up and/or throughput.

This author ranks the probability as quite low that Se could be added in a "fast" process to metallic precursor layers. Past work was carried out along these lines (Attar et al. 1994) . Similarly, advantages of CuSe or InSe precursors have not as yet been demonstrated to lead to high solar cell efficiencies (Anderson et al. 2003). In addition to films made by the former process having problematic mechanical film properties (flaking), rapid post-deposition selenization approaches have also not yet lead to great solar cell efficiency. This observation currently necessitates handling a high vapor pressure Se (relative low temperature) Se evaporation source and low vapor pressure Cu evaporation source (relative high evaporation temperature) in the same vacuum system.

CIGS PV showed the last significant "win-win" situation in PV when it was suggested (for reasons of lowering manufacturing cost) to change substrate material from using boro-silicate glasses to soda lime (ordinary window) glass. What was not anticipated was that such switch also increased the cell performance obtained. It is now understood that controlled addition of Na can enhance the performance seen in CIGS cells. In fact, Na addition was essential for making high-efficiency CIGS cells on metal foils a reality. The reasons for this advantage are poorly understood, but the observation is overwhelming that Na can improve CIGS solar cell performance.

The CIGS cell typically consists of the following structure: Glass/Mo-film/multi-stage-CIGS/CdS/TCO. Since a finished cell can be exposed only to moderate temperature (<200 °C, perhaps <150 °C), sputtered ITO or ZnO or LPCVD (Low Pressure Chemical Vapor deposited) ZnO are typically used as the TCO. The Mo-film and the TCO deposition processes may use more than one deposition process for fabricating such layer (e.g. sputtering condition). When using co-evaporation for the CIGS deposition process, the best performance results are obtained when substrate temperatures during the deposition process are high, approaching the softening point of glass. The CdS layer, for high

performing CIGS cells and modules, uses a wet (CBD chemical bath deposition) process for a thin (100 nm thick) CdS layer. For modules, scribing the p(1) through p(3) scribe lines can involve laser and/or mechanical methods (Tarrant & Gay, 1995). Because of a higher current density in CIGS (typically, 33 mA/cm² ± 15%) cell strips are typically only 5 to 6 mm wide. For such cells, scribing tolerances are particularly important for minimizing the non-contributing module area.

Many commercial CIGS modules are currently fabricated on rigid glass substrate/cover glass structures, limiting moisture ingress to the module perimeter. Even these structures initially had problems passing the damp heat (1000 hours at 85% relative humidity, 85 C) tests. This suggests that CIGS cells are more moisture sensitive than modules made using Si solar cells. Some commercial CIGS manufacturers fabricated on flexible metal foil material have therefore designed their cells as Si cell replacement to be packaged within glass sheets. The question has been posed whether such process could be inverted and/or be applied to flexible substrates. Flexible substrates (like polyimide foil) limit the temperature that can be used to deposit the CIGS films, but allow monolithic (scribed) integration of the module, while stainless steel substrates allow the use of higher deposition temperatures, but, because they are conductors, not the monolithic interconnection. Typically, PV made on metal foils is "slabbed" into individual solar cells, giving up some advantages of a roll-to-roll fabrication process.

In order to increase the humidity tolerance, it is presently not clear whether to make the solar cell more tolerant to moisture or whether to lower the water transmission rate of the module package. It is known that the ZnO layer used as the top contact by some entities deteriorates upon moisture contact. Some groups therefore work on replacing the TCO material. On the other hand, it is also known that there can be degradation for CIGS cell recipes that use an ITO instead of a ZnO contact for CIGS cells, and that other technologies (like a-Si or a-Si/nc-Si technologies) have achieved acceptable stability using ZnO for top and/or bottom solar cell contacts. It is somewhat likely that there is not a single cause or mechanism for moisture sensitivity, and that CIGS PV will be more sensitive to moisture than Si–based PV. This leaves the question how cost-competitive flexible CIGS is for power generation. Such competitiveness will require a light-weight, flexible and optically transparent low-cost moisture barrier. Acceptable barriers may exist as commercial prototypes, but commercial cost for such foils is not clear. If these foils were significantly more expensive than glass, the advantage of flexible CIGS PV could be diminished.

The long-term stability of CIGS is acceptable, depending on details of device processing and the quality of the package. Having been discovered some time ago, "transients" in CIGS-based devices are poorly understood. If finished solar cells or modules are exposed to moderate heat in the dark (<150 ºC, for example when modules are laminated), a power loss is often (but not always) observed. Such behavior is currently not predictable. Often, but not always, the power loss recovers when the module is exposed to natural or artificial light. These "transients" may change as modules age and pose a problem for qualification tests, specifying a pre-and post stress power variations that could be larger than stress induced power losses. For some CIGS pilot production modules, it was found that such transient loss effects were on the same order as stress or deployment induced losses. The question is to what degree recovery can be relied upon to achieve performance predictions that on average are correct?

Some tests (like the 85/85 test) heat the modules in the dark. Because of this behavior, the qualification test for modules utilizes the manufacturer's labeled module power rather than

the measured module power as the criterion for power loss upon stressing. CIGS (and all) thin-film modules are tested using the IEC 61646 accelerated testing specifications. One manufacturer exposed CIGS modules with questionable lamination power losses to actual sunlight to ascertain the amount of recovery.

Long-term potential limitations to CIGS PV are the limited availability of In metal. The use of In could be reduced by manufacturing thinner cells than the thicknesses used today. However, experimental and commercial reality is similar to what has been said about thin CdTe solar cells above, because materials cost for the semiconductor layer currently are low, typically best performance, not minimum thickness is used for commercial activities. It is also unclear if a competing technology, flat panel displays, will continue to use In (ITO) or will switch to a different TCO material. Being limited by In availability is not expected to be a problem until terawatts of CIGS PV modules have been fabricated. Another potential problem is customer acceptance. CIGS cells use a small amount of CdS in the buffer. Several entities have therefore developed alternative buffers to CdS (Contreras et al. 2003). Such work may be successful (but no performance improvements were yet found because of using alternative buffers), and it is of interest to note that a similar wet deposition process for best alternate junction partners also uses CBD. There are also efforts to develop CIGS-solar cells using earth-abundant non-toxic materials only. This requires replacing the In (and perhaps Ga) used in CIGS solar cells. A popular candidate is currently Zn ("CZTS" cells), and efficiencies near 9% were reported for such cells (Todorov et al. 2010). Using such alternative materials suffers from the fact that the "secret" of CIGS solar cell operation is not understood (why the device optimizer has to do what he has to do in order to attain high efficiency solar cells, why In, Ga and CBD CdS work extremely well). Researchers focus on materials that have appropriate optical properties, but appear to miss out on the important relevant electronic differences between CIGS and alternative materials.

Research issues for CIGS based solar cells are: Understanding the difficulties scaling up current champion cell recipes to commercial size, understanding the befits of incorporating Na into cell, understanding the stoichiometric requirements (In to Ga to Cu to Se concentration ratios, in combination with other parameters such as solar cell thickness, chemistry of buffer layers etc.), understanding 'transients' in solar cells, understanding the 'secrets' of In, Ga, Cu, Se, and Na required for achieving champion-level efficiencies, developing alternative buffer layers, and understanding how V_{OC}, FF and J_{SC} losses could be mitigated in cell using absorbers <1 micrometer thick. There is less focus on the quality of the back contact, but unless Mo is used as the contacting layer, cell results are typically much poorer. The secret of the Mo use should be part of understanding why current champion cell recipes have to be made the way that they are being made.

4. Status and challenges for amorphous silicon and micromorph solar cells and modules

Amorphous silicon constituted the first commercial thin-film PV module product. The process of making amorphous silicon solar cells and modules was first invented by the RCA and Energy Conversion Devices (ECD) laboratories (Catalano et al. 1982, Izu et al, 1993). There was also a strong push by Japanese Companies (Sanyo, Fuji, Cannon, Sharp, to name a few) for commercializing this PV technology. At the time, both power and consumer products were being developed.

Spectrum splitting multijunction solar cells were invented in Japan (Kuwano et al. 1982) and consequently developed at ECD (later, doing business under their Uni-Solar brand name)

and Solarex (later doing business as BP Solar, but in 2002, pulling out of all thin-film PV activities), and also in Japan and Europe. For a while, it was believed that this was the easiest pathway to achieving high-efficiency low-cost solar cells and modules. While multijunctions offer a theoretical efficiency advantage, the practical advantages are of a lesser degree. This is because in case of the a-Si-based multijunction cells, the subcells of the stack are not perfect in terms of their I(V) parameters. This has a beneficial aspect for energy generation, because as long as non-ideal subcells are stacked, one cannot invoke ideal mismatch factors when calculating mismatch for the stack (Chambouleyron and Alvarez, 1985). In fact, for multijunction III-V-based solar cells, it was shown that by managing the current flow through the stack (limiting the current by the top-cell), fill factors of the stack can well exceed the fill factor of the weakest cell in the stack (Wanlass & Albin, 2004).

Fabrication of a-Si:H solar cells and modules uses plasma enhanced chemical vapor deposition (PECVD). Typically, silane gas (SiH_4) (germane gas GeH_4 for a-SiGe:H layers) is piped into a deposition chamber near 1/1000 of one atmosphere, and by applying an rf frequency, hydrogenated amorphous silicon (hydrogenated amorphous silicon germanium alloy) layers are deposited. In many instances, the frequency of 13.56 MHz set aside for such applications was used to excite such plasma, but in the 1980s, it was reported that using higher frequencies could produce a-Si:H films and solar cells with slightly improved properties and/or higher deposition rates (Shah et al. 1988). The higher frequency deposition has been adopted by a few commercial companies. Amorphous silicon can be doped, typically with phosphorus or boron, by adding a phosphorus or boron containing gas to the gas mixture. Typically phosphine (PH_3) is used for n-type doping, while for p-type doping, B_2H_6, BF_3, and $B(CH_3)_3$ have been investigated among other doping gases.

The a-Si:H cells and modules are available in both substrate and superstrate configurations. Due to the relative low deposition temperature (200 ºC or less) the choice of substrate material is less driven by temperature capabilities, but rather by issues like substrate availability, cost, and commercial handling issues. Commercial cells are illuminated through the p-doped contact and are hence termed n-i-p structures in substrate configuration or p-i-n structures for superstrate configurations. For superstrate configurations, a commercial or in-house prepared TCO layer is coated with one or more p-i-n sequences. Illumination through the p-type contact is clearly enhancing cell performance. Glass superstrate modules are typically scribed and interconnected into 1 cm-wide cell strips, commonly using laser scribing and welding methods. When conductive substrates (like Uni-Solar's stainless steel) are used, individual cells are cut from the substrate. Methods have been found to contact the top-contact TCO layer in such cells to extract the substantial currents from large-area cells.

Amorphous silicon (a-Si:H) PV went to its so far highest market share in 1988, thereafter losing market share because a resurgent activity in crystalline Si PV and because a-Si:H based module efficiencies were quite low and did not achieve stabilized efficiency levels that were predicted then (15% efficient module efficiency was predicted to be achievable by the late 1990s). Amorphous silicon suffers from so called Staebler-Wronski degradation. The a-Si:H based solar cells and modules are made with greater "initial" efficiency at modest deposition temperature (say 200 ºC), but when the devices are exposed to light, a reduction of power (and all parameters like V_{OC}, FF, and J_{SC}) typically occurs. The exact amount of such loss depends on the details of device fabrication, but the effect is significant (say typically for commercial devices on the order of 30%). The Staebler-Wronski degradation can mostly be removed by annealing (for one hour or so) at temperatures of 130 C, but this temperature is greater than the normal operating temperature of PV modules and could

damage module components. The strongest tool for mitigating such degradation is keeping the intrinsic-a-Si:H absorber layer thin. In 1990/1991, the US a-Si program therefore asked that only "stabilized values" for material properties and solar cell efficiencies should be reported. The stabilization procedure was specified as light-soaking under one-sun light intensity for 1000 hours at a sample temperature of 50° C (Luft et al. 1992). This change had two consequences: (1) a reduction of cell efficiency values as initial value were previously reported; (2) establishment and study of light-soaking in the major amorphous silicon laboratories. While this procedure is now followed by most commercial manufacturers, it is tempting to report better initial values, which is sometimes done. There was a debate whether or not Staebler-Wronski degradation could be entirely eliminated. To date, no elimination scheme has proven successful, but, as mentioned earlier, the magnitude of the effect can be controlled. While for many years it was believed that initial and stabilized performance scaled, it is now clear that smaller initial performance may result in greater stabilized performance and vice versa.

Large-area PECVD deposition may result in non-uniform deposition because different amounts of electric field are available on the rf cathodes of the typically capacitive coupled flat plate reactors used, because the wave length of the rf frequency and the physical dimension of the electrodes become of comparable magnitude. This problem typically becomes larger when higher frequencies (smaller wavelengths) are used to excite the rf (or vhf) plasma. Another source of non-uniformity arises from the fact that the feed-in distribution ratios of the precursor gases (SiH_4, GeH_4 and H_2) can change (because of consumption) in large area systems. It should be noted that on the other hand, such consumption can lead to desirable grading, say of the Ge-content in a-SiGe:H layers (Guha et al. 1988). These issues can all be overcome, by using the appropriate or segmented electrodes and gas feed-ins for large-area deposition. In the early 1990s, SERI (Solar Energy Research Institute, before the organization became NREL in 1991) specified attaining a certain amount of thickness uniformity (typically, ±5%) for large-area a-Si:H deposits in its subcontracts. These uniformity specifications were typically met, but what wasn't realized then is that the conditions used for meeting the uniformity criteria may not have been the same leading to the most efficient modules.

The following points may be important to assess degradation mechanisms: (1) there are interrelated "slow" and "fast" components to the solar cell degradation (Lee et al. 1996); (2) wrong fundamental degradation models could be the culprit for not being able to eliminate or minimize degradation, resulting in inadequate stabilization and "unexpected" degradation of commercial module product. High light intensity and low exposure temperature as well as process details like hydrogen dilution can favor the formation of fast (or 'easy to anneal') degradation (Lee et al. 1996, von Roedern & DelCueto, 2000)). Operating temperatures of an a-Si:H module could affect the annealing and stabilization process. Hence, a typical a-Si:H arrays show greater efficiency in the summer than in winter. This behavior is opposite to many other PV technologies, where efficiencies during summer are lower than during winter because higher operating temperatures (such temperature behavior also holds for a-Si:H modules) results in lower module voltages for the same radiation level, hence lower module power. For a-Si:H modules, the annealing effect (increasing efficiency) must be often more significant than the temperature effect (lowering efficiency). It is of importance to note that degradation and continued outdoor exposure affects the temperature coefficients observed. Typically for a-Si:H modules, T-coefficients become less negative, sometimes even positive after prolonged exposure. A detailed study

how degradation affects the amount of degradation that is observed has been published (Whitaker et al. 1991).

There was a resurgence of a-Si:H activities after the year 2005 when big companies entered the a-Si module arena by making or adapting deposition lines for a-Si:H-based PV modules. Many researchers believed that this could result in a renaissance for a-Si:H PV. However, the question should be answered: how could this be the case when these companies used the same PECVD process that was researched for over 30 years for the deposition of a-Si:H PV modules? Several a-Si:H PV companies have recently given up on this technology. Is this because the economical circumstances were not right, or is it because performance and cost expectations for such modules could not be met? The reader must draw his or her own conclusion on this.

In the 1980s, it was proposed that changing the radio-frequency (to values greater than 13.56 MHz) could change the properties of a-Si:H and also facilitate the growth of nanocrystalline thin film (nc-Si:H) layers. The nc-Si:H layers can be grown when there is a high hydrogen dilution of the gas fed into a PECVD system (typically>98% H_2). Subsequently, nc-Si:H layers were investigated as absorber layers for a-Si:H-based solar cells. For more than 10 years, it is known that layers resulting in the highest solar cell efficiency are "mixed phase" (nanocrystallites of relative small size, typically << 50 nm in size), rather than those involving the largest grains and almost no "amorphous tissue" (Luysberg et al., 2001). Like for a-SiGe:H, it was found that the properties of nc-Si were not "quite good" enough for use in single junction solar cells. Hence, these layers are typically used as a-SiGe:H replacement in spectrum slitting multijunction solar cells. One group termed the word "micromorph" for such solar cells.

The micromorph solar cell constitutes a conundrum for the solar cell optimizer. Multijunction solar cells are to be approximately 'current matched.' A common target value for the current density in champion tandem multijunction solar cells is 13 mA/cm^2. This value is difficult to attain in the stabilized thin a-Si:H top junction. It remains to be seen if the field, if sustained, will gravitate to optically enhanced solar cell (Platz et al., 1997) or if a triple junction solar cell structure (having a current density of 8.7 mA/cm^2) will prevail. Since nc-Si:H absorber layers were developed later than a-SiGe:H, some promoters projected a greater efficiency potential for such layers than for a-SiGe:H absorbers. In reality, cell performance for multijunction cells containing a-SiGe:H and nc-Si:H is about the same (approximately 12% stabilized "total-area" efficiency). It has been suggested that the crystalline nature of the nc-Si:H layer would result in deposition rate independent properties of the nc-Si:H solar cell. Unfortunately, experimental observations could not support such prediction, nc-Si deposited at higher deposition rates (say >2 nm/sec) shows a significant loss in solar cell efficiency. Since optimum nc-Si:H cells are 1.5 to 2 microns thick (compared to 0.2 micrometer thick a-SiGe:H absorbers), deposition times for nc-Si:H absorbers are typically longer. This poses another decision for the solar module optimizer: Should one "trade" consumable cost (GeH$_4$ gas is expensive!) for even higher equipment capital cost ? The statement that currently a-SiGe:H and nc-Si:H solar cells and modules would have about the same efficiency is sometimes controversial (Yan et al., 2007). (An article in Photon International reported that while "micromorph" modules had a higher efficiency than a-Si:H modules, the plant size for micromorh deposition equipment was also greater than for a-Si:H module deposition. If the same amount of equipment was used, micromorph production will result in a lesser annual output than producing pure a-Si:H modules with the same deposition equipment.)

Some PV technologies have come under attack for using poisonous or harmful gases. There have also been reports that the use and release of system etching gases (NF_3 is typically used) could make Si-based PV less environmentally friendly, since etching gases like NF_3 possess a green-house gas potential about 20,000 times greater than CO_2. Photon International estimated that for an a-Si:H module factory, the greenhouse gas "pay-back" time could be twice as long as the energy pay-back time (pay-back time characterizes the avoided greenhouse gases or energy that is used to produce a PV system including the modules). The energy pay-back time for an a-Si:H PV array is on the order of 1 year. For crystalline Si PV the same issue may arise, as some PECVD systems used to deposit a "fire-through" a-SiN$_x$:H antireflection layers also use PECVD for depositing the a-SiN$_x$:H films in etch-cleaned PECVD chambers using NF_3. There are ways to mitigate the emission of NF_3; (1) avoid the use of NF_3 cleaning, or (2) use alternatives for etch-cleaning chambers like on-site generated F_2.

5. Status and challenges for crystalline silicon film solar cells and modules

It is intriguing to use crystalline Si films to make Si PV. There is a problem that when depositing such films, silicon may become loaded with impurities from the substrate material used. At one point in time, it was thought that this could be overcome by using Si as a substrate, for example, a Si ribbon material grown quickly. This approach has not proven successful, presumably because the crystalline Si films grow with different rates epitaxially on different substrate crystalline orientations. There is also the quest for using lower temperature substrate materials, but even a solid state recrystallization requires temperatures that exceeds soda-lime glass softening temperatures. Many groups using crystalline Si films have used, with some success, heavily doped mono-crystalline wafers, mullite (alumina) derivatives, pure graphite, multi-crystalline Si films, or specialty glasses to achieve deposition or recrystallization of crystalline Si films. For some of the foregoing substrate choices, differences in the thermal expansion coefficients of silicon and the substrate material can result in additional issues that need to be resolved. The Solar program of the US Department of Energy (DOE) projected that in the 1980s, Si PV would transition from wafers to films. Such transition, however, has not yet happened, because films still result in a rather low solar cell efficiency compared to wafer Si. Most people define film silicon less than 50 microns thick Si film on a foreign (non wafer Si) substrate as thin-film PV.

One device issue is the small voltage that is achievable using thin Si films. Values for V_{OC} near 600 mV have been reported, but typical values are lower than that, perhaps on the order of 500 mV or less. The low voltages and fill factors are a universal observation for thin cells, but many researchers focus on short-circuit current density (J_{SC}) for thin–absorber cells. This leads to the following question: Should one first tackle a loss of V_{OC} and FF in thin absorber cells, or should one begin tackling short-circuit current densities? In 1998, Dr. Jürgen Werner summarized Si film solar cell observations by plotting grain size on a logarithmic abscissa scale and voltage or efficiency on the ordinate. It was observed that a huge "valley" existed. For grain sizes between 10 nm and 1 millimeter, no good correlation could be observed between grain size and cell voltage or efficiency. In the 12 years following such plot, despite new experimental trials, not many new observations were added to Werner's original plot. This poses the question to what degree grain size could be an effective "driver" towards higher solar cell efficiency?

For many years, NREL had worked with the Astropower Corporation (Delaware, and its successor, GE) on developing thin crystalline Si solar cells and modules. They delivered

various cell and module prototypes. What was striking was that with about 30 micron thick absorbers, short circuit current densities (<28 mA/cm²)and QE responses were measured for such cells that were similar to champion light enhanced nanocrystalline nc-Si:H-cells were the absorber was only 1.5 to 2 microns thick. This poses the question to what degree the fall-off of the quantum efficiency red response is determined by incomplete carrier generation or by incomplete carrier collection or both? Thin Si PV is a perfect example demonstrating where reliance on the appropriate R&D assumptions will greatly affect the optimization efforts. If losses were due to incomplete carrier collection, one would gear optimization attempts towards reducing collection losses, while incomplete generation losses would be fixed by enhancing generation, typically by applying optical enhancement schemes. It is possible that measured QE responses are affected by both factors, while a majority of R&D efforts may have been conducted under the assumption to enhance generation in thin solar cells by researching optical enhancement techniques alone. It is currently not known what the potential of crystalline Si film solar cells is. The observations made during the last 30 years optimizing Si based solar cells could suggest that progress with thin Si film solar cells could be less likely and may not be attainable, if the observations rather than the expectations were correct.

A similar question should be asked for another case of crystalline Si PV, recrystallized amorphous silicon. Commercial development for crystalline Si film solar modules has occurred at Pacific Solar (later CSG, Crystalline Si on Glass, at one point in time, affiliated with Q-Cells, now belonging to Suntech Corporation). CSG modules achieved about the same performance level as amorphous silicon (a-Si:H) modules. CSG uses 2 micrometer thick layers for the absorber (a recrystallized a-Si precursor on a specialty glass substrate). This observation poses a very fundamental R&D question: "Was CSG not given enough resources to develop a better solar cell, or was the expectation erroneous that a better solar cell efficiencies would result from recrystallized 2 micrometer-thick crystalline silicon layers (recrystallized 2 micron thick amorphous silicon) than using 0.5 micron thick a-Si:H layers directly to produce a solar cell or module?" In order for fundamental science to impact technology, a more conclusive answer to this question has to be found.

6. Relating champion cell efficiencies and commercial module performance

Champion efficiencies are often used as the yardstick to gauge the PV status of a certain technology. It was found that the credibility of such numbers improves when champion results of independent testing laboratories are used, although several PV entities have developed internal procedures to obtain, within experimental uncertainty, the same results as independent testing laboratories. What is more controversial is that sometimes "unoptimized" solar cell results have been reported. In those instances, it is not clear what efficiency level might be attainable upon further cell optimization. As argued in the introduction section of this chapter and elsewhere, it is not clear if greater control and reduction in variability increases or decreases champion cell efficiencies. It is recommended that for the time being, either possibility should be considered as likely, namely that unoptimized device performance can or cannot be further improved after full optimization.

Champion solar cell efficiencies can be linked to current and future commercial module performance, based on what is known today about solar cell champion efficiency levels, which in recent years have not shown too much progress. In order to obtain current

Eff. (%)	Module	T.coeff. (power)	Technology	Current c/c performance ratio (module/cell eff.)
19.5	SunPower E19/318	-0.38 %/C	mono-Si, special junction, sp. j. (1)	78% (19.5/25.0)
17.1	Sanyo HIP-215N	-0.34 %/C	CZ-Si, "HIT," sp. J (1)	69% (17.1/25.0)
15.1	Suniva ART245-60	-0.46%/C	CZ-Si, sp. J. (2)	72% (15.1/21.0)
14.3	Kyocera KD235GX-LPB	-0.44%/C	MC-Si, standard junction (std. j.)	70% (14.3/20.4)
14.3	Solar World SW235/240	-0.45%/C	CZ-Si, std. j.	68% (14.3/21)
14.3	Solar World SW 220/240	-0.48%/C	MC-Si, std. j.	72% (14.3/20.4)
13.9	Solaria 230/210	-0.5 %/C	"standard" mono-Si cells, 2x concentration	65%* (13.9/21.5)
13.6	Suntech STP 225-20Wd	-.0.44%/C	MC or CZ-Si, std. j.	67% (13.6/20.4)
13.6	Evergreen Solar ES 195	-0.49%/C	String-ribbon-Si std. j.	65% **(13.6/20.4)
12.5	Q-Cells Q.smart UF 95	-(0.38 %+/-0.04)%/C	CIGS	62% (12.5/20.3)
11.5	First Solar FS-382	-0.25%/C	CdTe	69% (11.5/16.7)
11.9	Avancis 130 W	-0.45%/C	CIGS	59% (11.9/20.3)
10.1	Abound Solar AB62/72	-0.37 %/C	CdTe	60% (10.1/16.7)
10.0	Sharp NA-NA-V142H5/NA	-0.24%/C	a-Si/nc-Si	80% (10/12.5)
7.2	Uni-Solar PVL144	-0.21 %/C	a-Si, triple junction	60% (7.2/12.1)
6.3	Kaneka T-EC-120	n/a	a-Si single junction	62% (6.3/10.1)
1.7	Konarka Power Plastic 1140	+0.05%/C	organic	20% (1.7/8.3)

*There is no good published value for 2x concentrated cell performance. Here, the corresponding Solar cell efficiency is taken as 21.5%.
** There is some uncertainty whether or not string-ribbon Si can reach multicrystalline Si efficiencies, but this has been assumed.

Table 1. Module Efficiency from survey of manufacturers' websites and commercial module efficiency over champion cell efficiency ratios"

commercial performance, an internet survey provides some guidance as to what module products, and technologies are commercially available. Then the ratio between verified champion efficiency and module performance can be calculated. It is clear that commercially available module efficiencies have to be discounted from champion cell level efficiencies, and that module efficiencies are smaller than solar cell efficiencies. In 2006, this author used a "discount" of 20% between champion cells and commercial modules (von Roedern, 2006). Now, 5 years later, the data suggest that it would be very unlikely that average commercial module efficiencies could exceed 80% of the respective champion level solar cell efficiency. The most mature and selective technologies (wafer-Si) have not yet exceeded this (80%) value for even for their best commercial modules yet.

Table 1 shows a summary from February 2011 of commercially available PV modules. Only modules available on manufacturer's public websites for sale where the technology is identifiable are listed.

Using the 80% argument, it can then be estimated what maximum average commercial module efficiency is likely based on what is known about champion solar cells today. Table 2 provides such breakdown.

The point to be made is that there is a difference between champion cell and champion module efficiency (estimated to constitute an efficiency difference of about 20%). While some technologies may reach a high ratio earlier than others, current champion-cell efficiency numbers can be used to estimate future commercial module efficiencies. There are some claims that some modules perform better in hot environments than at low temperature. These real effects are on the order of +/- 10% in energy generation, but there are unknowns of similar magnitude like the degradation encountered over the system lifetime, the quality of the installation, the weather fluctuations, and the accuracy of the name-plate rating, to name a few factors.

Technology	Future commercial module performance (80% of current record cell efficiency)	Future Relative Performance	Future Relative-cost (using a 50% thin film cost advantage)
Silicon (non-stand)	19.8%	1.21	0.83(competitive)
Silicon (standard)	16.4%**	1.00	1.00 (reference)
Silicon (standard, 2x)	17.2%	1.05	0.71 (competitive)
CIS	16.2%	0.99	0.51 (highly competitive)
CdTe	13.2%	0.80	0.63 (highly competitive)
a-Si (1-j)	8.0%	0.49	1.02 (about the same)
a-Si (3-jj), (or a-Si/nc-Si)	9.8%	0.60	0.83 (competitive)

**Since there is only a marginal performance difference for standard cells using mono- or multi-Si wafers, an "average" champion cell performance of 20.5% was used to calculate standard Si module performance. 12.3% was used for spectrum splitting a-SiGe:H and nc-Si:H multijunctions

Table 2. Anticipated Future Module Efficiency and Relative Cost Based on Today's Demonstrated Champion Cell Performance

Low light-level efficiency values may look better for some modules then for others, but those higher low-light-level efficiencies can be lost after a module is deployed or stressed (Wohlgemuth 2010). Low light-level higher efficiency also affects the energy output differently in different climates. The more overcast the weather, the more important is lasting higher low light-level efficiency. The interactions between climate and energy output poses the question whether PV modules will get a single rating or a deployment site specific rating because modules are sold in STC Watts and revenues are received in terms of energy generated.

7. Notes on reliability and durability of thin-film modules

One of the most frequently questions asked is: How durable is this technology versus longer-established wafer-Si PV technology and whether or not Si PV would be "the

hallmark of stability" as these technologies are sometimes presented. Clearly, there are changes in all technologies, and as modules age or are stressed, transient behavior, power and temperature coefficients will change (Whitaker et al., 1991, del Cueto & von Roedern, 2006, Wohlgemuth, 2010). I sense some reluctance in the testing community to specify accelerated stress conditions, because not all effects and mechanisms for module degradation or failure are known, and because some people in that community hold out the hope that there would be better accelerated stress conditions that would better predict real world performance of modules. What is not realized is that there could also be a value for having standards, and that standard conditions will not reflect real-world conditions or energy generation. For example, the fuel economy of automobiles is based on standard tests, while the prudent driver will know that he or she may not achieve or exceed the standards because of their driving techniques and conditions differ. I advocate that it is the manufacturer's duty to assure durability, and that long-term durability depends to a large degree on whether or not an appropriate manufacturing process was used. Technology related instability problems with any PV technology are currently difficult to identify, and mistakes were made in all technologies leading to the observation of unacceptably high module failure rates. Newer technologies are apt to reveal greater failure rates for a while.

While glass to glass sealed modules are often being produced, glass breakage can lead to increased failures in thin film PV modules. Glass breakage and its mitigation are the topics of much research. Standards are sometimes helpful and sometimes misleading. For example, two sheets of annealed glass laminated with a layer of ethyl vinyl acetate (EVA) can pass the hailstone impact test (a 2.5 cm diameter hailstone impacting at terminal velocity, 23 m/s). This has led many module developers assume that if the hail test can be passed, the mechanical strength was acceptable. Yet, thermally induced glass breakage will occur. Given the observation that glass breakage is not so much a factor for crystalline Si PV modules, the use of partially strengthened or partially tempered glass is strongly recommend to be used for thin-film PV modules.

It is also well established that some forms of PV are much more moisture or oxygen sensitive than other technologies. Sensitivity to ingress of elements can be mitigated by either making the device (solar cell) less sensitive to the penetrating elements, or by better sealing the module package. In practice, both approaches may be used to result in the most cost-effective scheme to increase the durability of a PV module. Glass will not allow penetration of elements and provides a perfect seal, except for the edge glass to glass seal. This may not be the case for flexible schemes where flexible layers have to be used. While flexible opaque materials may provide neccessay low transmission rates and do not pose a glass breakage problem, other issues may become critical when there is a need to use optically transparent barrier foils for flexible PV modules. An early example that the quality of a "package" needs to accommodate the sensitivity of the device was provided when the tested packaging approach used by industry (for a-Si:H-based PV module technology) did not sufficiently protect flexible CIGS modules. In fact, it was determined that the established (a-Si:H) package should be labeled as 'breathable,' as water vapor diffuses rather quickly through Tefzel and EVA. If the device can endure such water vapor transmission, its stability may be acceptable. There are now pilot-quantity flexible transparent barrier materials for niche applications for more sensitive PV technologies (like CIGS) with much lower (and perhaps adequately low) water transmission rates. What is more difficult to evaluate is how those materials compare in terms of cost to glass.

Most systems today are assessed by their energy output. That adds a complication, because in some climates modules with cracked glass may continue to perform well for a number of months or even years. Because glass breakage is very evident, and because these broken modules are not likely to deliver guaranteed powers after many years and may present a safety problem, broken modules may get replaced before they cause a notable power loss. Similar arguments apply to the effect of delamination. If modules get replaced as soon as a visible defect appears, it may become more difficult to assess average long-term stability. An added problem is that it is hard to predict how delamination will progress. One thing to notice is that T-coefficients for power may become smaller negative (or for stabilized a-Si:H- or OPV-based PV even slightly positive) numbers as the modules are being deployed. Smaller than wafer Si PV negative temperature coefficients are typically viewed as something positive, as the derate going from an STC to a real world condition rating decreases. However, if the T-coefficient were to become a less negative number upon deployment, one has to keep in mind that the STC degradation may actually increase more rapidly than the outdoor data might suggest.

The testing community is looking to develop rapid tests that can reliably predict long-term module performance. Such development requires an understanding about all major mechanisms leading to long-term power loss. Only after individual mechanisms are known can there be an assessment how they will respond to acceleration. Then, perhaps more appropriate tests could be developed. In the mean time, much "infant mortality" of PV modules can be avoided by passing qualification tests. For example, when the "wet high potential test" (wet high pot) test was being implemented, modules having defects in the edge seal were identified and eliminated. While the wet high pot test was originally conceived out of safety concerns, it was also useful for eliminating early module failures. Further testing of leakage currents is important, and modules should perhaps be tested not only to the safety standard but rather to the lowest leakage current that can be measured for a specific module configuration. For wafer Si PV modules, much progress with respect to module durability was achieved by passing the JPL "block" tests that later resulted in the appropriate qualification test (e.g., IEC 61215, 61730). However, one should not forget that a module passing qualifications tests may fall below guaranteed (warranted) power in the field while modules that could not pass qualification tests may show acceptable durability upon long-term deployment (Wohlgemuth et al., 2006).

Further (beyond not understanding all mechanisms in detail), the accurate prediction of lifetime details is further encumbered by the statistical nature of the degradation behavior, leading to a spread in the observed data. Hence, rather than testing individual modules, statistically relevant identical module samples have to be assessed. The other issue is that outdoor conditions vary and cannot be in detail predicted. The latter observation poses the question whether module manufacturers will develop modules for specific climates, or whether there will be one product for all climates. Whether or not we will see differentiation in the modules for weather-specific sites will undoubtedly depend on the cost savings encountered if/when climate-specific modules are manufactured. Many industrial items, say automobiles or consumer electronics, are manufactured such that only a single quality standard and product exists. Customers like 'rankings' of items using standardized procedures or tests but do often not realize that if the difference between ranks is less than the uncertainty there may be statistically no difference between those ranks.

There cannot be absolute certainty about the warrantee period until such time has passed. Typical wafer Si PV guarantees given about 20 years ago correctly predicted that such modules or PV arrays would provide on average 80% or more of their initial rating. Today,

typically such power warrantee increased to 80% of minimum rated power output after 25 years. Manufactures give 'competitive' warranties, which in addition to technical reasons define the typical 25-year power warranty period. Since wafer Si PV is providing such guarantees, the competing thin-film PV companies have to do so as well. In the opinion of the author, such warranties will likely be met by many reputable manufacturers. However, the numbers are quite staggering. If in 2010 about 15 GW of PV were sold world-wide and if 1.5 GW of modules installed in 2010 required replacement before 2035 due to low power (assumption: 10% of modules require warranty replacement because of more than the guaranteed power loss has occurred), that is 5 million 300-W modules, and corresponds to the wattage manufactured in 2010 by one of the world's largest PV companies. While no predictions can be made with absolute certainty, it is somewhat likely that all enduring PV modules, including thin-film PV module technologies, will meet or exceed current limited power warranty of 80% after 25 years.

8. Outlook

Future development of PV technologies is uncertain. Table 2 provided the author's current outlook on efficiency and relative costs. It is difficult to project real PV costs far enough into the future. However, Table 2 also shows that projections are possible based on what is known today about specific PV technologies. Table 2 also provides an example of why it is important to make independently verified champion solar cells. "Champion" solar cell efficiency numbers provide historic continuity, as they have served as a "yardstick" to progress within each PV technology. Looking at crystalline Si PV, it is not clear if standard or non-standard approaches will gain or lose market share. Table 2 essentially says that if the cost reduction is proportional to an efficiency decrease, there is no net economical benefit.

Whenever observations do not confirm expectations, it is suggested to question expectations with the same scrutiny as observation (experimental results). The statistical nature of data needs to be realized; it should be always said what is being compared, best, average or worst data. For solar cell efficiencies, this requires an understanding to distinguish between best (champion) and average production efficiencies. Sometimes, advantages and disadvantages of a process change are not pointed out with the same scrutiny. Researchers have to ask themselves whether there should be further optimization of known factors, or if greater progress could be made being guided by unexpected or empirical results. Historic examples exist for new results being developed guided by a flawed theory (e.g., the invention of black powder) or the guidance of a correct theory could lead to unexpected results (Columbus discovering America while searching for a new route to India). It is especially important to keep observations and already established results in mind to avoid unnecessary repetition of experiments. Without this, unfruitful approaches to solar cell development could be tried anew.

It is important to realize the role of material science in this process. On one hand, it is known that higher quality materials can result in higher solar cell performance, while on the other hand it is also known that sometimes the incorporation of "inferior" material layers resulted in champion level efficiency cells. The use of CBD CdS, resistive TCO, and polycrystalline, non-stoichiometric, Na-laden CIGS films on glass rather than single crystal CIGS makes that point. It is well known that solar cell optimization is "interactive," i.e., when one layer in a cell is improved, other layers may need to be reoptimized. For example, when the TCO layer

in an a-Si:H-based solar cells were switched from SnO_2 to ZnO, the p-layer deposition conditions also had to be reoptimized to obtain the highest efficiency solar cell or module after such switch. A fundamental answer has to be found for the following question: Why is a high-lifetime mono-crystalline silicon wafer easily processed into a low efficiency solar cell? In addition, the following question requires an answer: "Is there a single set of parameters defining stabilized champion solar cells, or are multiple combinations of materials and solar cell parameters (V_{OC}, J_{SC}, and FF) capable of reaching champion level cell efficiencies? Recent observation in the case of CIGS solar cells suggests that there could be indeed multiple optima.

The proprietary nature sometimes hurts the development of correct models. For example, to correctly identify the stability mechanisms in solar cells or modules, all processing detail may have to be known. Often, companies do not wish to make such knowledge public. In these instances, it appears most effective to bring together researchers in a conference or workshop setting to discuss as much of a problem as is possible.

It is not clear which technologies will "win" in the long run. Thin films have a cost advantage over crystalline Si, provided the durability is comparable and the performance is high enough. Arguments were presented that the benefit from moving from wafer Si to thin film products can be calculated.

9. Acknowledgement

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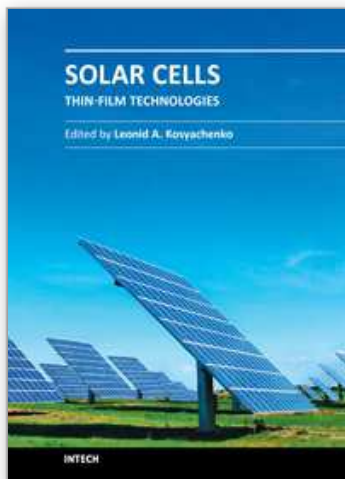
Solar Cells - Thin-Film Technologies

Edited by Prof. Leonid A. Kosyachenko

The first book of this four-volume edition is dedicated to one of the most promising areas of photovoltaics, which has already reached a large-scale production of the second-generation thin-film solar modules and has resulted in building the powerful solar plants in several countries around the world. Thin-film technologies using direct-gap semiconductors such as CIGS and CdTe offer the lowest manufacturing costs and are becoming more prevalent in the industry allowing to improve manufacturability of the production at significantly larger scales than for wafer or ribbon Si modules. It is only a matter of time before thin films like CIGS and CdTe will replace wafer-based silicon solar cells as the dominant photovoltaic technology. Photoelectric efficiency of thin-film solar modules is still far from the theoretical limit. The scientific and technological problems of increasing this key parameter of the solar cell are discussed in several chapters of this volume.

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