CRITICAL NATIONAL NEED IDEA

NEW APPROACHES TOWARD MAKING THIN FILM SOLAR CELLS COST COMPETITIVE

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Transformational changes are required to meet growing energy needs

Reducing greenhouse gas emissions is a global problem that requires significant changes on how energy is generated, distributed and consumed. This is not only a domestic issue but needs to be addressed on a global scale. The Energy Information Administration (EIA) of the DOE projects that in the period 2005–2030, energy consumption in developed nations will grow by 19 percent, while developing nations will increase their energy consumption by 85 percent (EIA-DOE 2008c). Altogether, world energy consumption is expected to grow by 50 percent over that 25 year period[1].

“Enabling renewable energy to achieve its potential in the U.S. energy mix will require a long-term, consistent policy approach to address cost, regulatory, and transmission infrastructure challenges. For solar photovoltaic (PV) technology, basic research is particularly important to make the needed improvements in cost and performance”[2]. “The long-term prosperity of the United States depends on continued innovation in technologies for electric power generation”[3]

Why photovoltaics? There was a time when this was a difficult question to answer. Fossil fuel was plentiful and apparently without end, and the earth’s environment appeared resilient. The photovoltaic (PV) industry was based on the niche applications of powering satellites and remote locations. However, the tide has dramatically changed, with growing recognition of the environmental impact of non-renewable energy sources and the economic volatility that comes from reliance on oil and gas.

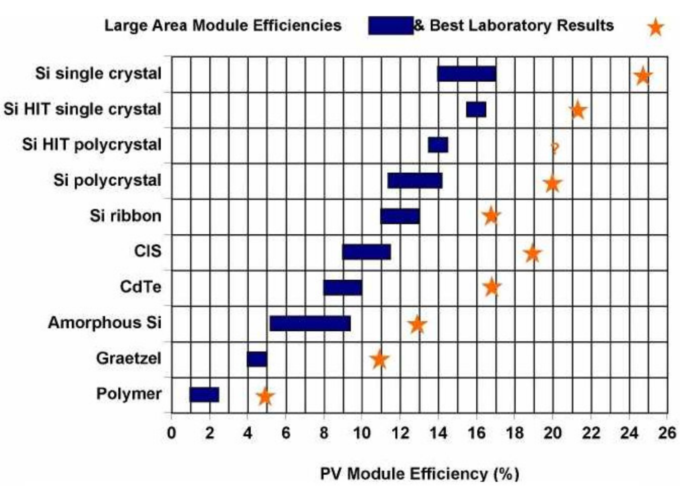

Figure 1. Typical solar module efficiency versus the best achieved laboratory results for different PV technologies. Courtesy to www.solarnavigator.net

The PV technology faces a number of challenges to make the solar energy cost competitive with traditional energy. Direct manufacturing cost ($/m^2) and conversion efficiency are the factors that determine module cost in $/Wp. Solar panels are still far away from the cost goal of $0.33/ W_p set by DoE[4] This is the cost at which PVs will start being an attractive alternative without government subsidies. However, the current average cost is $2.3-2.5/$W_p$. The targeted goal of $0.33/$W_p$ can be achieved through solar

[1] Energy Information Administration, United States Department of Energy (EIA-DOE). 2008a. Annual energy outlook 2008. Washington, DC: EIA. DOE/EIA-0383(2008). http://www.eia.doe.gov/oiaf/aeo/;
[2] Ibid, pg. 2;
[3] Ibid, pg. 4;
[4] K. Zweibel, Solar Energy Materials & Solar Cells, 63 (2000), 375-386;

panels having efficiency of ~15% (currently below 10% in average) and manufacturing costs of about $50/m^2. The total module costs are currently around $100/m^2 for thin film PVs and about $200-$300/m^2 for silicon wafer PVs. Therefore, significant improvements are required to both increase the products' conversion efficiency and reduce their manufacturing costs in order to reach these goals.

Figure 1 reveals one of the most critical issues with the solar cell manufacturing technology. As new manufacturing technologies are developed (see the vertical axis), there is a growing difference between the achieved manufacturing conversion efficiency of the products (black bars) and the best laboratory results, attained for selected samples (stars). In most cases this difference is as large as 8-10%. This efficiency reserve is sufficient to achieve the 15% target efficiency set by DoE.

Obviously, the gap between the manufactured products' efficiency and the best-achieved performance for selected samples is largely due to deficiencies in the manufacturing process.

This white paper is focused on the solar cell manufacturing. It specifically discusses some manufacturing improvements that are needed to make the next second and third generation thin film photovoltaic (PV) solar cells competitive with traditional energy sources.

The Manufacturing Technologies

Currently there are two generations of PV technology being already deployed. First generation PV cells are single-junction solar cells based on silicon wafers including poly-crystalline (p-Si) and single crystal (c-Si). Historically they gained more than 90% world market share while p-Si accounts for 63% of world market. First generation cells have efficiencies around 8-15%, even though efficiencies as high as 24% are reported for selected c-Si laboratory samples. While silicon based solar cells are already a mature technology first deployed in the early 70's, there are still manufacturing inefficiencies responsible for the efficiency gap. These manufacturing inefficiencies are mainly due to insufficient manufacturing yield and non-uniformity of the PV parameters over large module areas. The main problem with this first generation PV technology today, however, is the material cost, which makes up to 40-50% of the total cost of the finished module. The cost of silicon wafers needed for manufacturing solar cells is very high and the industry must compete with the demands of the large semiconductor industry.

Second-generation or thin film PVs, use significantly less material and has the potential to be manufactured in less time (in a few hours in some cases) significantly reducing the manufacturing costs. Most recently, we've seen whopping investments into the thin film solar cell sector, including $300 million for Nanosolar, $104 million for Ava Solar, and $100M for HelioVolt. In early 2008 the market analysts predicted that thin films will account for a big portion of the solar market in just a few years and would capture up to 40 percent market share by 2012. That 40 percent figure is higher than the levels predicted just two six months ago and is more in-line with the focus of president Obama's energy policy. In July 2008, for example, Lux Research predicted that thin film solar panels would make up 28 percent of the total solar power market in 2012, reaching sales of $19.7 billion (out of total $70.3Billion market predicted for 2012). The newest predictions are that the thin film solar cell market would reach $28.1 billion by 2012 and will exceed $77 Billion in 2015 (77% of the predicted $100 billion market in 2015). These predictions assume that some time in 2013 the thin film solar cell manufacturing will catch up and then exceed the traditional silicon wafer-based manufacturing.

The thin film solar cell technology is based predominantly on deposited amorphous silicon (a-Si) thin films, $CuInSe_2$ (CIS), and its higher band gap variant $Cu(In/Ga)Se_2$ (CIGS) and CdTe (and any of these with S replacing Se or Te). Thin film solar cells can be manufactured at very low cost by using simple and well-developed methods such as vacuum deposition (First Solar, DayStar Technologies, Miasolé, HelioVolt, Solyndra, Xunlight), printing (Nanosolar, ISET, Ascent Solar, Solarmer Energy) and electroplating (SoloPower, Stion). The thin film solar cells use much less deposition material and can be deposited on a variety of low cost substrates as stainless steel and flexible surfaces (foils).

A special quality of the $Cu(In,Ga)Se_2$ (CIGS) material is its variable bandgap, which can be changed by varying the Ga/(Ga+In) ratio[5]. This quality is used to optimize the general bandgap level as well as to develop different multi-junction solar cells, which are considered the third generation solar cells. The third generation solar cells are the multi-junction solar cells, made of GaInP, GaAs, and Ge, which have bandgaps of 1.8 eV, 1.4 eV, and 0.7 eV, respectively. In monolithic multi-junction solar cells, the different semiconductor layers are grown directly on top of the other layers using the same substrate. As a result of this method, the lattice constant must be the same for all of the layers. A lattice mismatch as small as 0.01% (~0.05Å) significantly affects the career mobility and decreases the current produced by the solar cell[6].

Need for Improved Coating Process Diagnostics and Control

All solar cell manufacturing processes suffer from manufacturing inefficiencies that currently lead to lower quality or inferior cells with lower efficiency measures. This results in a lower yield for the high efficiency products. While some silicon- and CdTe-based companies are able to achieve higher manufacturing yields, the CIGS-based companies struggle on a daily basis with the problem of thin film non-uniformity and other parameters variances over the deposited substrates, which significantly degrade their manufacturing yield.

The uniformity issue puts significant limitations on the manufacturing of thin film solar cells, specifically CIGS.

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[5] O.H. Lundberg, Upsala University, *PhD thesis*, 2004
[6] S. Lansel, Progress report, School ECE, Georgia Inst. of Technology, April 2005

- **Limits the size of the deposited substrates**. Few CIGS manufacturers in the world can achieve reasonably high manufacturing yield (> 90%) on glass panels of 120 x 60 cm square.
- **Limits the width of the deposited rollers** and makes depositing coating on 120 cm wide rollers inefficient.
- **Reduces the deposition rate** and **wastes expensive materials** due to the needs for special shadow masks.
- **Requires very large deposition chambers** in order to get a uniform coating across a large substrate. This increases the **initial cost** of the manufacturing equipment as well as increases the **operation costs** of the equipment. The larger chambers require more time and energy to achieve the needed vacuum and deposition thickness and require more manufacturing floor space.

Lower manufacturing quality results in lower efficiencies and higher product costs. In some cases, the product is unsuitable for assembly into a finished module and must be rejected and disposed of. The safe disposal of the rejects is also a part of the problem and bears additional waste of energy (all Cd-based products are toxic). Next generation solar products such as high efficiency multi-junction solar cells, nanotechnology-based products and photonic crystals experience even lower yields resulting from the inability of the traditional process control technologies to maintain parameter uniformity over large substrate area. Since the next generation thin film solar cells will be thinner, uniformity becomes even more important and requires real time monitoring and control at several places on the deposited substrate.

Thin film deposition is a complex process requiring thorough control of the process parameters and in many cases additional control of film characteristics, such as optical, electrical, thermal properties, and mechanical stresses in the film, while maintaining geometrically, stoichiometrically and structurally uniform films.

A well known engineering phenomenon is that the film formation processes typically "drift" over time, causing the deposited films to gradually deviate from their target values[7,8]. This deviation is expressed not only in a gradual change of film parameters over time, but also on different areas on the substrate. The non-uniformity appears not only as variances in the film thickness but also as variances in film properties from spot to spot on the substrate. These non-uniformities have to be detected and corrected in real time, or the products gradually fall outside their targeted specification. This problem is specifically severe in the case of manufacturing solar cells, which in most cases uses long manufacturing processes and large deposited substrates.

[7] A. Schwarm et al., US Patent 7,201,936, 2007;
[8] T. Reiss et al., US Patent 7,337,019, 2008;

One of the many reasons for the process “drift” over time is the overcoat of the processing chamber walls during the process, causing changes in the thermal, optical and electrical properties and their distribution inside the chamber. For example, deposition of a dielectric layer on the chamber walls during the process may gradually change the electrical conductivity and/or isolation properties of the process-surrounding area or create temperature gradients which can gradually change the quality of the deposited films not only in time but also from location to location on the substrate. Another reason for drift in the thin film process parameters is the change in the temperature, pressure, current or other parameters due to the fact that the measurement sensors change their properties during the process. A simple example is the deposition of material on a thermocouple during the deposition process, which changes the thermal capacity and, therefore, the temperature reading of the thermocouple. Similar is the case with thermal imaging cameras. A typical example of drift is due to the wearing off of the sputtering target as the material is depleted, which changes the spatial distribution of the sputtered particles. Another example is the decrease of evaporated material in the thermal boat (effusion cell), which causes gradual overheating of the boat and therefore, changes the deposition rate.

Furthermore, because the effective temperature on the surface, where the film is deposited (or etched), is different than the ambient temperature (due to the excessive kinetic energy which the deposition or etching particles deliver to the surface), it is difficult to precisely model the local condition, at which the thin film is formed or removed.

As a result of these and other issues, the local conditions are constantly changing in a non-uniform manner throughout the process, affecting the thin film properties and, therefore, the manufacturing yield.

Many modifications of the typical thin film formation processes are made in order to partially mitigate the effect of process parameters drift. In some ion assisted deposition processes the growing film is bombarded with ions and accelerated particles that supply additional kinetic energy to the surface and enhance the surface mobility of the deposited material particles to improve film growth. However, this approach is not considered a viable approach in the deposition of semiconductor layers such as sulphides, selenides and tellurides and large area substrates. Another solution to the problem is the application of different bias voltages which can modify the particle distribution during deposition and enhance the formation of the film. In some other cases application of simple shadow masks at the right time and position can improve the film uniformity and increase the manufacturing yield. All these are not low-cost solutions.

Some thin film PV deposition systems and manufacturing lines are commercially available (manufacturers are Applied Materials, Oerlicon, Veeco, etc.). These systems and lines are developed mainly for manufacturing of the more traditional α-Si-based thin film solar cells. In reality most manufacturers of thin film solar cells today (and practically all CIGS-based manufacturers) build their own thin film deposition equipment to reflect the specificity of their technology and their know how[9,10,11,12]. However, in almost all cases, the process control systems, added to their equipment, are usually based on traditional Cole-Palmer, Inficon, RKC, Telemark, etc. process controllers and control systems originally built for other applications.

This traditional state-of-the-art process control systems integrate over time and/or space the measured process parameter values (such as temperature, pressure, current density, bias voltage, gas flow, etc.) and try to keep them constant or within certain tolerances. In most cases, specifically in the PV thin film processes, there is no constant monitoring of the deposited PV structure and no decision process based on what is really taking place on the substrate. In other cases there is some in-situ / in-line process control, usually restricted to measuring the mass (or rate) of the deposited material. Process control solutions involving real time plasma diagnostics, such as absorption / emission spectroscopy, are also available. These control and monitoring methods do not provide sufficient information about the property of the film under deposition and its distribution over the substrate area, or they provide information too late in the process, when the film is already deposited.

The result is a low quality product with lower efficiencies and a wide statistical distribution of properties even among those products that are able to meet the product specifications.

Different control schemes are devised to address the non-uniformity and parameter drift problems. Run-to-run control, in-line feedback control, and fault detection control attempt to reduce non-uniformity and increase the efficiency of manufacturing by measuring the outcome of the process “post factum” by correcting the process for the next sample, next run or next batch. As for the measured sample, it is usually rejected.

Current monitoring (if any) and control technologies are designed in a way that they “judge” the product being manufactured, rather than manage it. They measure products on a “pass/fail”, step-by-step or run-to-run basis. The individual monitoring detectors (ellipsometers, end-point detectors, etc) usually leave the decision making process to the engineer. Errors in the manufactured product are discovered too late to be corrected for the failed sample and can be corrected only for the next sample. When the products fall outside the acceptable tolerances they are rejected and the process controls are modified for the next batch of product. The traditional systems are bulky, inaccurate, expensive and sensitive to noises and vibrations. Using current technologies, thin film producers see lower quality cells in 10 -15% of their manufactured product resulting in several hundred millions of dollars of lost revenue.

[9] D. R. Hollard, US Pat. 6,974,976, 2005 (Miasole);
[10] M. Keshner et al., US Pat.7,264,849, 2007 (OptiSolar);
[11] J. Tuttle et al., US Pat.7,319,190, 2008 (Daystar Technologies);
[12] G. Faykosh et al., US Pat. 6,719,848, 2004 (First Solar);

The “post factum” control puts limitations on the process control accuracy. It increases the cost of the manufactured goods and wastes energy. Such a control is particularly inadequate when new generation products are manufactured such as nanostructures, photonic crystals, and high efficiency solar cells.

Research needs to be conducted in the area of real time, in-situ process control. This additional level of process control can provide the real time feedback needed to improve the manufacturing process and reduce material costs. This will result in higher PV efficiencies and help reduce overall module costs.

Currently, only a few techniques are in practice, based on changes of reflectance from the growing film surface, and in-situ monitoring of composition using X-ray fluorescence. The following table show some of the most frequently used monitoring techniques used in the thin film industry.

Needed feature	**RHEED***	**In-situ AFM***	**End-point detection/ Reflectometry**	**Spectroscopic Ellipsometry**	**Scatterometry**	**Plasma Emission/ Absorption Spectroscopy**	**X-Ray Fluorescence**
Non-invasive			√	√	√	√	√
Precise	√		√	√	√		
Easy to install			√				
In-situ/In-line	√	√	√	√		√	√
Measures in real time			√			√	
Monitors products directly	√	√	√	√	√		√
Monitors more than one parameter							
Monitors optical scattering					√		
Monitors moving samples							
Monitors many spots simultaneously							
Developed for PV specifics			*R&D*	*R&D*		√	√
** RHEED: Reflective High Energy Electron Diffraction; AFM: Atomic Force Microscopy*							

It becomes clear that, while there are many methods which can potentially be deployed to perform real time property monitoring of the PV film under deposition, few of them are actually applicable to the current thin film solar cell manufacturing. This situation is entirely different compared to other thin film technologies such as optical and semiconductor thin film technologies. Tools must be developed that can respond to rapid processing and feedback for adjusting real-time processes. This real time process control will result in increased quality, throughput and yield, and will make the process reproducible and reliable.

Research in Area of In-Situ Process Control

Most viable practical solution to the problem with parameter drift during deposition of PV thin films is to monitor and control the deposited film at many spots in real time and provide immediate correction in case of deviation. This can be realized by deploying optical monitoring of the reflectance, transmittance, polarization properties, optical scattering and its angular distribution.

Manufacturing deviations resulting in a lower quality product can be significantly reduced by deploying intelligent optical real time product control using a system that follows the product as it is manufactured and corrects it in real time to keep it within its specification (guides the product "on autopilot"). In some way such a system should be focused on the product specification and be able to modify the product design for subsequent layers in real time when it detects deviations from the final product specification. This means that once a deviation is detected the system will be able to simulate in real time the effect of the error on the product specification and optimize the remaining layers in order to return the product to its specification. As a last measure such a system can issue a command to the traditional control system to change some of the process parameters (*this has to be avoided, if possible, because of the time-delay and the "ripple" effects such a change always has*).

Since such an intelligent control systems require the installation of several monitoring and control units in one deposition machine, it would also be too expensive to deploy traditional monitoring and control solutions such as traditional ellipsometers or end-point detectors / reflectometers. In order to enable the development of intelligent optical control system for solar cell manufacturing, **a new type of optical sensor**[13] is needed which is able to acquire local information about the sample under deposition in very close proximity to the surface of the specimen.

A critical parameter in controlling the thin film solar cells is the value of **optical scattering** during deposition, which is very closely related to the most important film parameters such as surface and interface roughness, optical absorption, crystalline structure and grain boundary size, anisotropy, porosity, carrier diffusion length, and, thus, the efficiency of the solar cell. This monitoring has to be performed in a wide spectral range, including extreme ultraviolet (EUV) and deep ultraviolet (DUV). Traditional monitoring of scattering from outside the deposition chamber does not produce adequate results for this purpose because scattering has to be measured in close proximity to the surface. There are no currently available technical solutions, able to provide information about the film scattering and its angular distribution in real time as the films are deposited.

[13] See for example G. Atanasov, US Pat. 7,345,765, 2008;

Stimulates the Nation's Scientific Frontiers

Research in thin film PV industry and more specifically in improving manufacturing processes is extremely important and will push scientific research to new heights. Improvements in thin film manufacturing will improve our nation's competiveness against international manufacturers who are increasing their annual market share.

Process control systems are well understood and enjoy a level of maturity in many industries but have not been fully utilized in the thin film PV industry. The technology used in other manufacturing industries can be leveraged to ensure success for this industry.

Meets a Timely Need not Met by Others

Addressing the nation's as well as the world's growing energy needs is of vital importance and cannot be deferred due to the global warming crisis. Research in PV technology and specifically in improving manufacturing issues associated with making PV technology affordable and cost effective is critically important. Government funding of this transformational research is required to ensure success and cannot be solely met through private investments. The specific issues of process control improvement are not currently being funded by other federal agencies.

Delivers the Potential for Impacts and Transformations

TIP funding is required to advance research in this area. Improving process control systems will lead to more efficient manufacturing processes resulting in increased PV efficiencies and lower costs. This will in turn lower the total cost of ownership for solar cells allowing them to be an attractive alternative to traditional energy sources. This transformational change from relying on fossil fuel to using the most abundant energy source available, the sun, can only be accomplished through federal research investment.

Through improvements in manufacturing processes, it is feasible for the solar industry to be competitive with traditional energy sources as soon as 2012. This will have a dramatic impact on our carbon footprint and will help reduce global warming. It will position USA to be a world leader in the generation of low-cost alternative energy through better utilization of solar energy.