

Intelligent optical control for manufacturing of large size thin film solar panels

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Significant improvement and technology innovation is required to both increase conversion efficiency and reduce the manufacturing costs of the thin film solar panels. This is the challenge that led to the development of the intelligent optical control system, described here.

Manufacturing innovation is needed in the thin film PV industry

Although the long term prospect for solar energy is very good, PV technology faces a number of short term challenges to make solar energy cost competitive with traditional energy.

Solar cells are measured by how much they cost for the power they produce (\$/W), so the way to make them more affordable is to reduce their manufacturing cost and/or increase the power they generate. The thin film PV technology offers the potential to significantly lower manufacturing costs well below \$1/W. The thin film solar technology today is based on amorphous silicon (a-Si), CdTe or Cu(In/Ga)Se₂ – CIGS, and is the most rapidly growing solar technology. It is expected that it is able to bring the solar energy to parity with the traditional energy some time by 2013. The problem

today, however, is that thin film solar panels are too expensive for many areas and wouldn't be installed without government subsidies. There is a very large gap between the efficiency the manufacturers can achieve in their daily production (typically below 10%) versus the efficiency achieved in the lab (typically >18%) as shown in Figure 1.

The real time intelligent optical monitoring and control of the solar panels during manufacturing is viewed as a necessary step towards closing this ~8% efficiency gap between what can be achieved in a lab versus the typical efficiencies achieved in a production environment.

Shortcomings and Solutions

Today, solar panels and flexible rolls enter high vacuum and high temperature vacuum chambers, move from one chamber compartments to the next (separate

chambers are also used) and exit after all the solar thin films are deposited. In some cases, the individual panel can be stationary during the process of deposition, but in other cases the panel or the flexible roll is constantly moving.

It is widely perceived that there are some issues associated with the manufacturing control of thin film solar panels.

All solar cell manufacturing processes suffer from manufacturing flaws resulting in lower quality solar panels and higher cost. While some silicon and CdTe-based technologies are able to achieve higher manufacturing yields, the CIGS-based technology struggles on a daily basis with the problem of thin film non-uniformity and other parameter variances over the deposited substrates, which significantly degrade the manufacturing yield. These non-uniformities and deficiencies have to be detected and corrected in real time, or the prod-

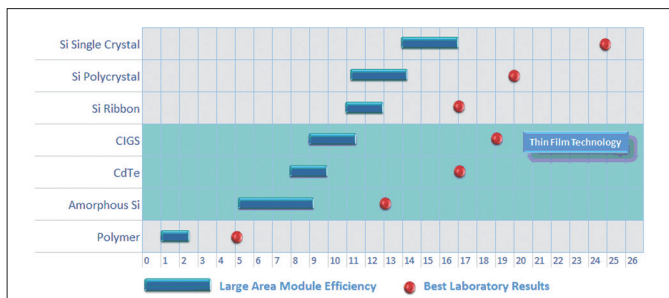
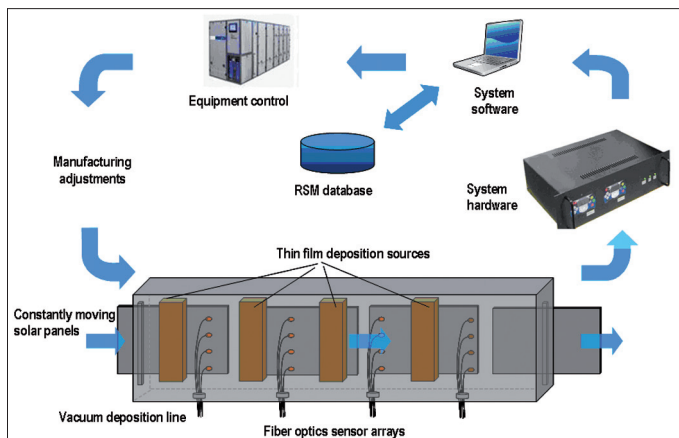


Figure 1: Large area solar panel efficiency achieved in the manufacturing versus the best results achieved in laboratory environment.



On the right, Figure 2: Intelligent real time optical control during solar panel depositions provides for timely detection of thin film deficiencies and immediate manufacturing adjustment for each individual panel.

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ucts gradually fall outside their targeted specification. This problem is also severe in the manufacturing of next generation multi-junction thin film solar panels.

There are very few available real time quality control systems able to control film uniformity and homogeneity on moving panels inside the manufacturing line. In all cases the control is done after some individual film or all films are deposited and the panel is already moved outside the deposition compartment or chamber. If deviations or non-homogeneity are detected at that stage, it is not possible to correct them for the current panel and for all or most of the other panels that are already under deposition inside the chamber.

The available in-situ monitoring and control systems typically "judge" the product "post-factum". The individual in-situ optical monitoring systems (Ellipsometry, X-ray Fluorescence, Photo and Electroluminescence, etc) are too slow for real time process control and adjustment. As a result, errors in the manufactured product are discovered too late to be corrected for the failed panel/batch and can only corrected for the next panel/batch. Such an approach wastes materials and energy and increases the product cost, delaying the achievement of parity. It will hardly be possible to tune such a run-to-run control to produce waste-free manufacturing. The problem is often mitigated by over-designing the product to meet even tighter tolerances in order to guarantee that the final specification will be met with reasonable manufacturing yield. The over-designing of the products additionally wastes materials and energy.

The real time optical control

The optical control system, described here, is based on measuring the physical properties of the layers in real time as they are being made. It provides real time analysis and correction not only for the current layer being deposited, but also makes recommendations on how to modify the future layers to accommodate the imperfections in the current layer.

The control system is based on miniature fiber optic sensors installed at specific points in existing equipment

without disrupting the manufacturing process. The miniaturization of the sensors allows positioning of the sensor in very close proximity to the deposited surface and monitoring the specular and diffuse spectral reflectance R from the film as the substrate moves throughout the deposition chamber (Figure 2).

Monitoring of the diffuse component of the spectral reflectance is an important feature, required for two main reasons.

First, the measurement of spectral scattering allows the calculation of haze, defined as¹:

$$H_R = R_{diffuse} / R_{total}$$

The scalar scattering theory relates the haze to the surface roughness δ_{rms} of the film by:

$$H_R = 1 - \exp\left[-\left(\frac{4 \cdot \pi \cdot \delta_{rms}}{\lambda}\right)^2\right]$$

where λ is the wavelength. The surface roughness is an important parameter related to the film morphology and is responsible for the light trapping inside the absorber. It was shown that increasing the surface roughness can reduce significantly the thickness of CIGS films for the same absorptance².

Second, monitoring of the diffuse component of the spectral reflectance is needed to accurately calculate the absorption coefficient $\alpha \text{ (cm}^{-1}\text{)} = f(E)$, from which the material bandgap E_g of the thin film can be calculated. This is particularly important for amorphous silicon solar films, which have relatively high bandgap energy, at which significant scattering loss is present.

The determination of the material bandgap from simple spectral reflectance or transmittance measurement of the thin film does not produce accurate results. The absorber thin film exhibits interference patterns in the spectral vicinity of the bandgap (the Urbach zone), which prevents the correct definition of the bandgap energy. More accurate determination can be done by using absorption

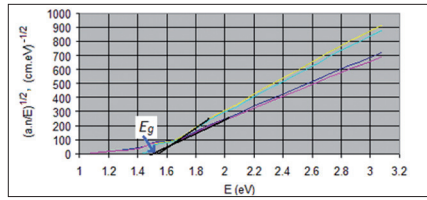


Figure 3: The energy bandgap of the film under depositions is found by extrapolation of the linear portion of the curve onto the energy axis.

coefficient extrapolations³. The Cody's relationship⁴ provides good linear extrapolation (Figure 3) and is represented as:

$$\sqrt{\alpha \cdot n / E} = B(E - E_g)$$

where α is the absorption coefficient, n is the film refractive index, E is the photon energy, E_g is the bandgap, and B is a constant.

The intelligent feature

Since the sensors are positioned at many different locations along the manufacturing line in both parallel and series configurations and are controlled by the same software program, the intelligent control system is able to record complete product histories and keep the best product results in a large database of response surface models (RSM).

The primary motivation for creating a RSM is to predict a system's output (the solar panel quality) corresponding to a given set of manufacturing conditions, or to determine in advance the necessary conditions that would yield a desired product quality. For example, consider a chemical vapor deposition reactor system with M process inputs \mathbf{x} (e.g., temperature, precursor gas composition, flow rate, etc.) that produces thin-film solar cells with N measured outputs \mathbf{y} (film thickness, chemical composition, bandgap, surface roughness, etc.). In the case where the process inputs \mathbf{x} are held constant over the deposition cycle, the response surface model is actually a set of M nonlinear equations in the vector form

$$\mathbf{y}(t) = \mathbf{f}(\mathbf{x}, t)$$

The actual RSM take the form of simple polynomials and can be thought of as a Taylor's series expansion of the ac-

tual function (which remains unknown) about some nominal set of process input parameters:

$$\mathbf{y}(t) = \mathbf{b}_0(t) + \mathbf{b}_1(t)\mathbf{x}_1 + \mathbf{b}_2(t)\mathbf{x}_2 + \dots + \mathbf{b}_{1,1}(t)\mathbf{x}_1^2 + \mathbf{b}_{1,2}(t)\mathbf{x}_1\mathbf{x}_2 + \mathbf{b}_{2,2}(t)\mathbf{x}_2^2 + \dots$$

During the product manufacturing the objective is to find the process inputs \mathbf{x} that result in desired panel qualities. Symbolically we can express this in terms of inverting the set of process models

$$\mathbf{x}_{set} = \mathbf{f}^{-1}(\mathbf{y}_{set}, t) \text{ for } j=1, \dots, J.$$

In cases when $\mathbf{x} \neq \mathbf{y}$ the inverse operation results in an optimization problem in which an objective function is minimized⁵.

By deploying intelligent features in real time, the system is able to detect ongoing problems, find the solution in its database, adopt the adequate RSM and validate the result for the same panel without human involvement. It is able to automatically guide the thin film formation process even as the parameters such as pressure, temperature, currents, and other deposition parameters fluctuate or drift throughout the process. The solar panels always come out of production optimized with better efficiency.

The described system does not replace the control systems, which are already installed by the equipment manufacturer and are in use, but adds one more layer of control, which typically takes care of all minor deviations during the process. The system eliminates unnecessary "test runs" and in some applications the "point-to-point" diagnostics and "run-to-run" control.

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1. Haze is wavelength dependent, but often is defined as average over the spectrum
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