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# NEW PARADIGM FOR REAL-TIME MEASUREMENT AND MAPPING IN a-Si:H/μc-Si:H TANDEM DEVICES

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ABSTRACT: Thin-film Si solar module production requires a fast wide area tool for layer characteristic measurement and control. Non-uniformity in layer deposition is expected to induce loss in module power. Simulations of amorphous Si modules using a two-dimensional model have been used to examine the efficiency loss associated with non uniformity of large scale monolithically integrated thin film modules. The results indicate that non uniform deposition significantly lowers the module efficiency, in a magnitude that varies depending on the shape and orientation of the deposition signature relative to the scribe lines. In order to control the deposition process of individual layers in layer stacks in thin-film PV modules a wide area metrology tools has been developed and tested. Example of layers maps obtained during production of Si layers module are shown. Comparisons of layer characteristics obtained using this tool and values obtained by conventional methods are given to validate the tool performances.

Keywords: a-Si:H, micro crystalline silicon, tandem, module production, quality control.

## 1 INTRODUCTION

Fabrication of efficient and reliable thin-film silicon solar modules requires the deposition of each layer (TCO, doped and intrinsic layers and back contacts) with good uniformity in terms of thickness and material characteristics. Quality controls of the deposited layers are usually performed by off-line instruments on a few glass plates and corrective actions are then taken to improve the production process.

Reproducible deposition of uniform layers both in terms of thickness and material properties is of paramount importance for achieving the highest photovoltaic module conversion efficiency. The effect of local defects or local non uniformities have already been studied in the past [1,2] but those related to non uniform layer characteristic (spatial variations over the full module size) have so far been overlooked.

In order to improve throughput, to identify problems as early as possible and to fine tune the fabrication process, it would be desirable to provide inline tools for the characterization and full-panel mapping of each of the layers included in a solar cell stack. In a-Si:H/μc-Si:H tandem solar cells, the deposition of the intrinsic layer of the bottom μc-Si:H cell is rather critical, especially on full size glass panels (Gen 5 or Gen 8.5). Achieving a uniform deposition of the μc-Si:H layers with a given crystallinity value and at a high growth rate is a challenge. A fast and reliable process control and metrology tool, capable of performing full module scans at an acquisition speed compatible with production rates, would be highly desirable.

With optical characterization in the visible and infra-red domain, one can access, given the appropriate optical model, many useful layer characteristics. Brightview Systems has successfully developed a unique wide area metrology tool (Brightview's Insight$^{TM}$) that allows very fast and accurate acquisition and full size module mapping of the module properties [3]. With the proper optical models and algorithms, thickness and roughness characteristics of layers such as TCO and a-Si:H and μc-Si:H, can be determined individually by measuring the full layer stack. Brightview's Insight$^{TM}$ can map a full size module (1.1x1.3 $m^2$ or 2.2x2.6 $m^2$ Gen 8.5 modules) on the fly, at speeds compatible with the current tact time of a production line.

In this paper, we first present a numerical simulation based study on the effect of deposition uniformity on the PV module conversion efficiency. This work focuses on several cases representative of typical non-uniformities arising in thin-film PV modules production. The simulation model was calibrated using the parameters of a typical Gen 8.5 single-junction a-Si:H module; however the conclusion applies, in a qualitative way, to other type of thin-film modules. The results underline the need for wide area metrology tools, such as Brightview's Insight$^{TM}$. Examples of the latter capabilities obtained on production like PV modules are then presented. These are complemented by a set of measurements performed by the tool on a set of controlled test samples deposited in R&D deposition equipments. This particular set was tailored to exhibit a wide range of material characteristics much broader than those found in production modules.

## 2 SIMULATION MODEL

For the simulation, the module is described as a two-dimensional matrix of individual cells, connected by resistors. The properties of each cell can be specified independently of the other cells. Figure 1 shows a typical simulated module, where the thick black lines indicate the scribe lines of the monolithical serial interconnections, and the dotted thin lines indicate numerically separated parts of the same electrical cell. The thick brown lines at the lower and upper parts of the figure represent metal short-circuiting elements connecting the transverse cells (i.e. the module bus bars). For the sake of simplicity the results reported in this page are based on modules comprising a 30x30 array of cells.

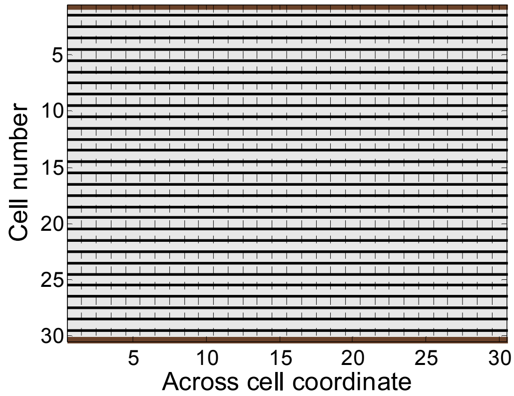


**Figure 1**: A large scale module modeled as a 30x30 cell array.

The electrical model used for a single cell is the traditional single-diode Shockley model. While this model is known to be approximate, its accuracy is satisfactory for the purpose of the current study. Figure 2 shows the electrical model of the single cell. It contains 3 elements connected in parallel – a current source $I_{SC}$, a Shockley diode D, and a shunting resistor $R_{SHUNT}$. It is further connected through series resistances ($R_{SERIES}$, $R_{SERIES,trans}$) to the neighboring cells.

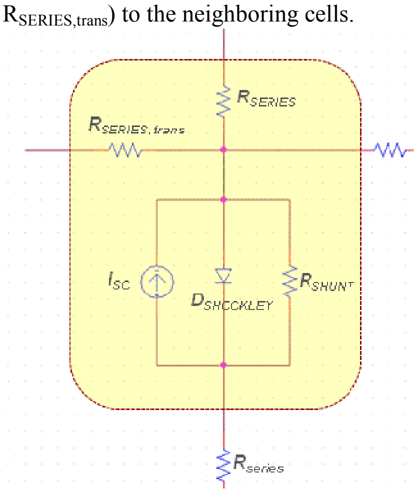


**Figure 2**: The electrical model of a single cell

The values of the electrical components characteristics used in the model were determined by fitting the results to a typical IV curve of a ½ production Gen 8.5 module. Figure 3 shows the experimental curve alongside the fitted model. The experimental curve was scaled by 130 in the voltage axis and by 220 in the current axis to represent a single 1x1 $cm^2$ cell. The fitted parameters were: $I_{SC}$=14.1 mA, $R_{SHUNT}$= 500 Ω, $R_{SERIES}$=0.7 Ω. The diode was represented by the Schockley diode equation $I=I_0 exp(-qV/nk_BT)$ where $I_0=4\cdot10^{-9}$ A, n=1.9, T=300 K and $k_B$ is the Boltzman constant. For the full array model, the transverse resistance connections were taken to be the same as the monolithical connection series resistance.

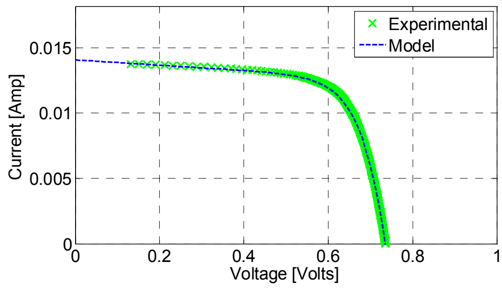


**Figure 3**: Fitting of a single diode model to an experimental IV curve.

## 3 SIMULATION RESULTS

Simulations were performed using WinSpice™ simulation software. We here report on the effect of the short circuit current $I_{SC}$ non uniformity on the module efficiency. We have simulated 5 cases: one ideal uniform deposition and 4 typical non uniform $I_{SC}$ distributions, all following Gaussian shaped signatures, either centered or shifted. The different signatures are presented in figure 4. They were all normalized to the same averaged $I_{SC}$ value with a 5% relative standard deviation.

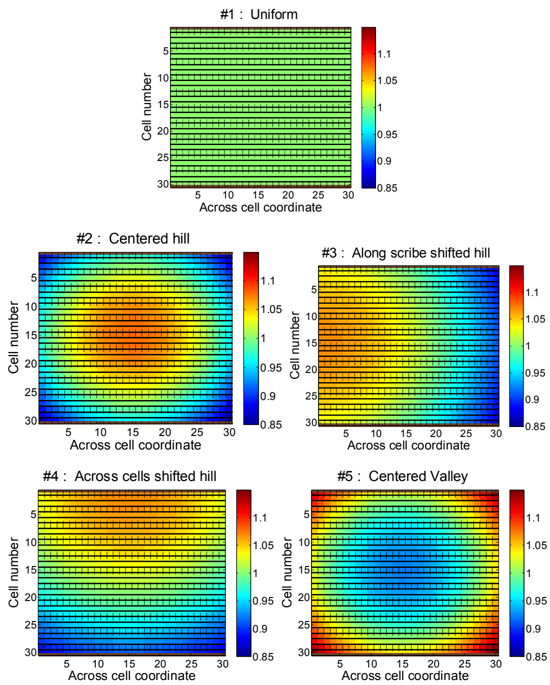


**Figure 4**: The simulated deposition signatures.

The IV results are shown in figure 5, where the graph is zoomed to focus on the maximum power point of the I(V) characteristics. The relative power loss associated with each signature is provided in the graph legend. As can be seen, signature #4 results in the highest power loss – 2.1%. This is expected as such non uniformity in $I_{SC}$ generates the largest variation between the different series-connected cells separated by the scribe-lines.

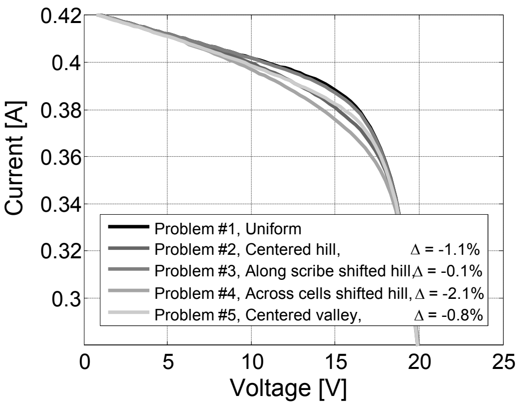


**Figure 5**: The IV curves of the different simulated modules.

## 4 MAPPING OF MODULES

Examples of mapping of layer properties with Brightview's Insight$^{TM}$ tool, as obtained in a single measurement of the layer stack, are shown below. In Fig. 6, one can see maps of the normalized TCO layer thickness and a-Si:H layer thickness and roughness, as measured on a glass/TCO/a-Si:H stack on a production module. All these parameters can be independently deduced from a single measurement. Maps are obtained by scanning the entire module under the measurement probes

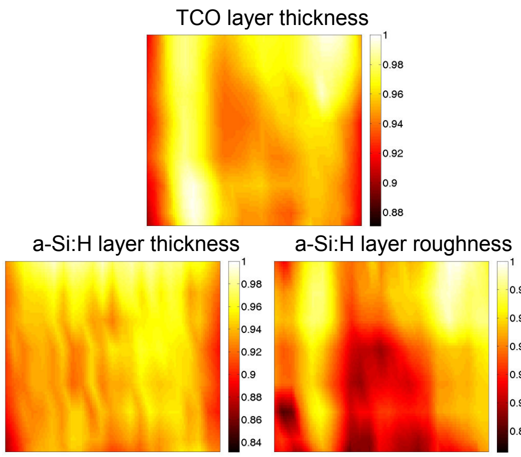


**Figure 6**: Normalized front TCO layer thickness and a-Si:H layer thickness and roughness maps of a full size module as measured on a glass/TCO/a-Si:H layer stack.

Individual layer map can also be determined from the measurement of glass/TCO/a-Si:H/µc-Si:H layer stack as deposited during the fabrication of a-Si:H/µc-Si:H tandem modules (cf. Fig. 8). TCO and the Si stack thickness and roughness can be obtained. Reliable separation of a-Si:H and µc-Si:H layer characteristics (when the full stack is measured) is not yet part of the Insight tool capabilities. However, this tool is capable of producing crystallinity maps of the µc-Si:H layer.

From the measurements of TCO layers, as deposited on glass or as a back contact, sheet resistance maps, as measured optically (see also Fig. 9 in section 4), can be obtained. This "optical" sheet resistance is representative of the TCO material quality in the grains and does not take into account possible effect of the grain boundaries [3]. For modules comprising a back thick ZnO contact, the thickness, roughness and sheet resistance of the latter can also be mapped reliably. Furthermore the Insight$^{TM}$ tool is also able to produce Haze and total transmittance maps. Note that the latters are deduced from optical modeling without the use of an integration sphere.

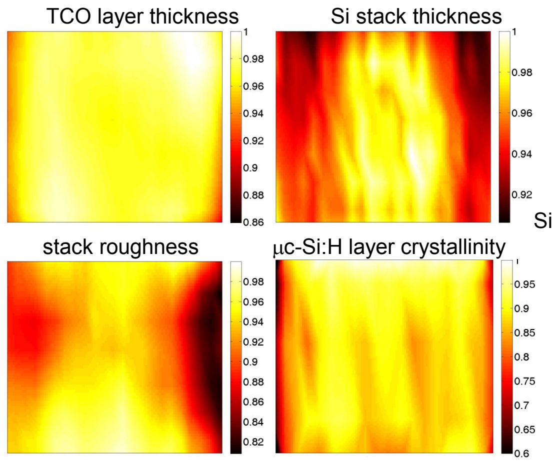


**Figure 7**: Normalized front TCO layer thickness, a-Si:H/µc-Si:H stack thickness and roughness and µc-Si:H layer crystallinity maps of a full size module as measured on a glass/TCO/a-Si:H/µc-Si:H layer stack.

## 5 OPTICAL MODEL AND TOOL VALIDATION

Calibration of the optical model as well as the validation of the Insight$^{TM}$ tool has been performed by measurements on a large variety of layers and layer stack exhibiting a very wide variation of thickness and material properties. Note that the variations studied exceeded by far what could be expected in a production environment. These samples were deposited in R&D small area reactors as well as an industrial KAI R&D reactors. Various types of TCOs such as various commercial $SnO_2$ layers on glass and ZnO layers on glass have been used for this calibration and validation work. Good agreements between the conventional measurements and the value deduced by the tool are obtained. Examples of the comparison of ZnO layer thickness and roughness as obtained optically using the Insight$^{TM}$ tool and using a profilometer and an atomic force microscope (AFM) are given in Fig. 8. Similar correlations were obtained also for a-Si:H or µc-Si:H layer deposited on glass but also as deposited on a TCO layer.

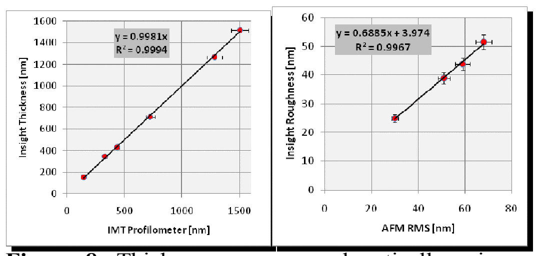


**Figure 8**: Thickness as measured optically using as a function of profilometer thickness measurements (left) and roughness (optical measurement) as a function of AFM roughness measurement (right) on a thickness series of ZnO deposited by low pressure CVD.

Other validation steps of Insight$^{TM}$ were performed on full size production modules. For example, maps of layer thickness and properties such as those shown in Fig. 6 and 7 were also characterized by conventional methods and satisfactory agreements were observed. Using optical means, TCO sheet resistance can also be mapped and here also a very satisfactory correlation is obtained between the “optical” value and the value measured by 4 point probes technique (cf. Fig. 9). ). In principal, one expects a difference between the "optical" and "electrical" sheet resistance values due to additional grain boundary resistance, not seen by the optical technique [4]. For the production modules investigated so far, as seen in figure 9, this inter-grain resistance is in most cases negligible and thus the optical result coincides with that measured by electrical transport.

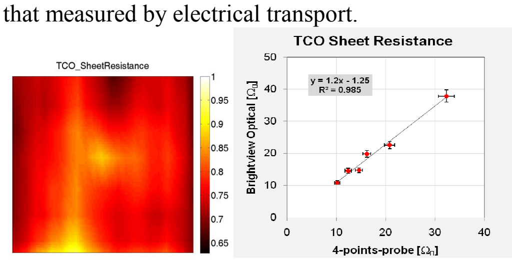


**Figure 9**: Normalized front TCO layer “optical” sheet resistance map of a full size production module (left) and (right) comparison of the sheet resistance measured optically and the values determined by 4 point probe measurement.

## 5 CONCLUSIONS

Non-uniformities in layer characteristics in PV modules can affect significantly the module performance. This paper studied, using electrical simulations, the effect of current non uniformities across large scale thin films modules. The results confirm that a non uniformity reduces the module’s efficiency, with an extent that depends on the spatial signatures shape and orientation. Production of large scale modules should rely on such simulation approaches to optimize the spatial variation of the layers properties such as thickness, roughness, crystallinity, etc, as these variations lead to changes in the current distribution and hence affect the overall efficiency. The effect of specific material property inhomogeneities should be more systematically studied in order to get a more quantitative view of the effect of a given signature in any of the module layer on the device performance.

More specifically, inline process control tools, such as Brightview’s Insight$^{TM}$, capable of wide area, high resolution spatial mapping of the layers properties are essential to control and optimize the production process.

Future research will study the effects of the other electrical parameters, as well as expand the solution to other thin-film module types, such an Silicon tandem and triple junction modules, CdTe and CIGS based cells.

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