

Workshop Report from the Thin Film Photovoltaic Symposium: Substrates, Contacts, and Monolithic Integration

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SUMMARY

Substrates and contacts play a critical role in thin film solar cell device and module performance. They influence light trapping, film growth, impurity levels, doping, stability, yield and laser scribing for monolithic integration. The substrate is also a major cost factor, often accounting for the largest component of the module cost. The interaction between the substrates or contacts with the semiconductor layers can also limit the range of the subsequent semiconductor layer processing parameters. The panel and audience discussed these factors in relation to fabrication, performance and characterization of today's thin film solar cells and modules.

INTRODUCTION

Why are substrates and contacts crucial for thin film photovoltaic module performance? Thin film solar cells must be deposited on substrates for mechanical strength. The substrate must be inexpensive, and relatively inert to all subsequent processing steps. In superstrate device designs, the substrate (typically glass) must allow light in with a minimum of optical losses. In every thin film solar cell, at least one contact must be transparent as well as conductive since it must transmit light into the semiconductor layers. Finally, both substrates and contacts must be compatible with monolithic integration to allow series interconnection. Modules have higher losses than small area laboratory cells due to the need for interconnections and for encapsulation. Table I lists some module losses for different thin film solar technologies. The magnitude of these losses will certainly depend on details of the device design and fabrication. They are given as representative values for purposes of discussion.

The interactive workshop was held at the Thin Film Photovoltaic Symposium at the University of Delaware on May 1, 1997. The workshop on the topic

"Substrates, Contacts and Monolithic Integration" was lead by Steven Hegedus of the Institute of Energy Conversion (IEC). Panel members and their topics were: Scot Albright of Golden Photon, Inc. (GPI) who discussed how substrate, contact and interconnections limit the performance of CdTe modules; Steven Hegedus of the IEC who presented unresolved issues on the electrical contact losses of textured ZnO vs SnO₂ substrates for a-Si devices; Frank Jeffrey of Iowa Thin Film (ITFT) who discussed lamination and substrate handling issues for a-Si modules on flexible plastic substrates; Tom McMahon of National Renewable Energy Lab (NREL) who described the range of characterization techniques available for diagnosing thin film module degradation and failure modes; and Scott Wiedeman of Global Solar Energy (GSE) who presented how substrate and contact materials limit Cu(InGa)Se₂ (CIGS) module performance. A brief discussion of the key issues outlined by each panelist is given below, followed by the ensuing dialogue between the audience and the panel.

CdTe/CdS Module Loss Analysis: A breakdown of the loss analysis of CdTe modules made by GPI is shown in Table I. Presently, 31 Watt modules have a total area efficiency of 8.3%, aperture area efficiency of 9.2%, and active area efficiency of 10.8%. Small area devices can be made from these modules having >13% efficiency. Table I shows that active area losses are the largest single loss, followed by transparent conductive oxide (TCO) and glass absorption. Different scribing and interconnect geometry is required to reduce interconnect area losses. The cell strip width must then be reoptimized. Glass absorption is a cost issue since low Fe glass or thinner glass would have less absorption but they either cost more or reduce yield. (Small area laboratory cells are typically on thinner, less absorbing glass which is another loss factor which occurs when scaling up from cells to modules.) Glass is also the most expensive component of the module. TCO absorption loss is

a trade-off with lateral sheet resistance loss. Reducing glass and TCO absorption each by a factor of 2 would improve today's module by 10% (assuming no increase in sheet resistance). Albright also discussed statistics of uniformity and process control. He estimated that development and application of on-line rapid diagnostic monitoring would improve the statistical process control leading to 15-20% gain in module output. Development of these diagnostic techniques are areas where universities can contribute.

Transparent Conducting Oxide Contacts for a-Si Devices: It is well known that although textured $\text{SnO}_2:\text{F}$ is the industry standard for superstrate (glass/TCO/p-i-n/metal) type a-Si solar cells, it has two weaknesses. First, SnO_2 is chemically reduced by H or SiH_4 plasma which leaves a thin layer of Sn which reduces its transmission. Second, SnO_2 has only about 93-95% internal transmission over the visible spectrum. In comparison, textured ZnO has been shown to be plasma resistant and to have 96-97% transmission over the visible spectrum⁵. However, electrical performance of ZnO/p-i-n cells is generally poorer than SnO_2 /p-i-n cells. It is nearly universally found that devices deposited on textured ZnO tend to have lower FF and/or V_{oc} , suggesting a poor electrical contact to the p-type a-SiC layer, but no fundamental studies have been made. Hegedus presented single junction a-Si device results comparing two ZnO substrates with identical structural, optical and electrical properties⁶. Both textured ZnO layers were deposited by LPCVD under similar conditions in different industrial laboratories, and provided to IEC for device studies. Table II shows results from the two ZnO substrates (called A and B) and compared to results on a SnO_2 substrate. All devices were co-deposited in the same a-Si run. Obviously, bulk structural, optical and electrical properties were insufficient to predict how ZnO A and B would perform in an a-Si solar cell. Unresolved questions from this and other TCO experiments are:

- Why such differences between otherwise identical ZnO A and ZnO B substrates?
- Why does ZnO often give poorer V_{oc} , FF compared to SnO_2 ? This prevents taking advantage of higher transmission through ZnO since the efficiency is lower.
- What determines ZnO/Si contact or junction properties?
- Can ZnO become a viable substrate for large area a-Si modules?

Encapsulation and Module Assembly: Several thin film technologies are based on deposition on a flexible continuously moving substrate. Some of the module assembly steps and materials are different from those developed for glass or rigid frame modules. Jeffrey discussed how processes and materials used in lamination and bonding need further improvements in cost, speed, and durability. These areas lack the allure and excitement of semiconductor processing and are often neglected by researchers, but they are critical production-limiting and performance-limiting areas. For example, vacuum lamination is well-established and compatible with EVA and other thermal bonding layers, but is very slow. It requires the roll-to-roll process to halt and each module must be cut up and handled separately, thus losing the speed and manufacturability inherent in continuous roll-to-roll processing. Roll lamination, however, is well established for other applications such as the sign industry, has high throughput, but little application to PV. Its compatibility with PV materials is unknown. Pressure sensitive adhesives (PSAs) are another crucial step for low-cost flexible module encapsulation. Three adhesive materials have been considered. EVA has good optical performance, is moderately expensive, but is not suitable for roll-to-roll lamination. Silicone-based materials have good performance but are expensive. Acrylics have had variable performance and UV resistance but are low cost. Evaluation of these materials for PV applications is complex. The thin

film PV industry, especially those based on flexible substrates, would benefit from assistance in developing new techniques or applying existing standards to a range of available materials.

Thin Film Module Diagnostics: Thin film modules can suffer from problems unique to the thin film PV technology as well as from problems common to standard crystalline Si modules. McMahon has developed and applied a range of non-destructive diagnostic tests to thin film PV modules. They are independent of the specific semiconductor materials in the module. Generally, they test the integrity of contacts and interconnections. These tests are useful in comparing one module process to another, and to identify failure mechanisms during extended life testing.

First order evaluation includes photographs, dark resistance at 0 Volts, and light and dark JV from reverse bias of at least -20% V_{oc} to forward bias of 20% beyond V_{oc} . Questions arising from first order evaluation leads to specific second order tests. For example, is low J_{sc} or V_{oc} for the module due to one shorted cell or all cells having slightly lower J_{sc} or V_{oc} ? Are changes in the apparent shunt resistance (slope at $V=0$) due to decreased shunt resistance or increased recombination? Are changes in apparent series or shunt resistance due to one cell or all, or is it really a change in the reverse diode characteristic? Ultimately, it is necessary to determine whether failures are cell-related or interconnect-related in order to change the appropriate processing steps.

Second order evaluation methods include two terminal shunt resistances⁷ to find the shunt resistance of each cell. OBIC-type spot scanning at a range of frequencies allows separate identification of each cell's photocurrent and shunt resistance.⁸ Internal series resistance of cells can be measured using an a.c. focused beam.⁹ Although not applicable to standard modules, special test structures can be fabricated to identify the location of undesirable second junctions or high contact

resistance.¹⁰ Finally, modeling series interconnected solar cells with lumped circuit model programs like PSPICE is useful to verify the source of the degradation.

Transparent Conducting Oxide Contacts for CIGS Modules: Since CIGS generates a higher current density than other thin film technologies, lateral series resistance losses in the top TCO contact are of great concern. However, the selection of the top TCO resistivity has an impact on the optimum CIGS bandgap as follows: higher TCO doping, while leading to lower TCO sheet resistance, also leads to higher free carrier absorption in the near infrared, which increases photocurrent losses as the CIGS bandgap decreases. Thus, the overall module design has the usual trade-off between the TCO resistivity and transmission, plus an influence on optimum absorber layer bandgap.¹¹ A figure of merit has been proposed¹² to rate TCO materials as a top contact (typically a thickness independent quantity given by the inverse of the product of sheet resistivity R_{sh} with absorption A). CIGS module performance would greatly benefit from a TCO material with $R_{sh} < 4$ Ohms/sq and $A < 10\%$ over the range 400-1100 nm, hence a figure of merit of 2.5. Although several TCO's have been reported with even better figures of merit, they have not resulted in better CIGS solar cell performance. In many cases this is because the TCO deposition parameters are incompatible with previously deposited contacts or absorber layers. TCO processes are needed which offer low cost, high deposition rates, low processing temperatures, and which use low toxicity materials. Often, TCO properties are degraded when integrated into a solar cell. Two specific problems with the top TCO layer were mentioned. First, top TCO contact properties depend on the underlying layers they are deposited on. For example, Wiedeman has shown that sputtered ZnO properties are worse when deposited on CdS compared to glass substrates, and that thick CdS is worse than thin CdS.¹³ Second, properties of the top TCO films are worse than bulk material properties. For example, the

mobility of bulk ZnO is $180 \text{ cm}^2/\text{V}\cdot\text{s}$ while that of thin film ZnO is $<50 \text{ cm}^2/\text{V}\cdot\text{s}$. Alternative materials and better understanding of TCO thin films grown by various methods and the effect of the underlying substrate layers would be useful contributions by universities.

DISCUSSION

A summary of the discussion is given here, not in the order in which it occurred but grouped according to topic. Audience members are not identified.

Since both Albright and Wiedeman pointed out that the selection of contacts and design of a thin film module were a trade-off between optical and electrical losses, it was asked whether better modeling and analysis would be helpful. A spreadsheet or model, which calculated the change in active areas with a number of laser scribes and converted TCO transparency and sheet resistance into an optimum cell width by minimizing power losses, would help guide the optimization. Such a program could be very generic and be applicable to all thin film modules. The panel members agreed that the present level of module loss modeling within their organizations was acceptable but could be improved. It was pointed out that factors other than simply maximizing power output were important to consider. The number of shunts per length and costs were crucial to making decisions about layer thicknesses, line widths and TCO materials. These are best done by each industrial group. It was also noted that there is very little university research or other published work on laser scribing; yet it is obviously a critical component for successful thin film solar modules. Thus, it is difficult to assess what the issues are and how universities can play a role in improving laser scribing and interconnections.

It was suggested that impurities in the glass or the ZnO could have been responsible for the differences reported by Hegedus between ZnO A and B. It is

known that Na diffusion varies with glass type and influences CIGS device performance. Although SiO₂ diffusion barriers are standard between glass and SnO₂, it was not known whether the ZnO layers had any diffusion barriers. Other panelists suggested that the standard SiO₂ is not the most reliable barrier, and that they see Na spikes even with commercial SnO₂ having SiO₂ barriers. It was generally concluded that more research at universities would be useful on inexpensive chemical diffusion barriers for glass or other substrates.

Although there is room for improving the figure of merit for existing TCO materials like ZnO and ITO for CIGS solar cell top contacts, new materials hold significant promise. It was stressed that for the figure of merit to be valid, it must be a weighted average over the appropriate wavelength range. Recent reports indicate that Cd₂SnO₄, Zn₂SnO₄, and CdIn₂O₄ have excellent figures of merit. A lengthy discussion of the properties of Cd₂SnO₄ and CdIn₂O₄ followed. These materials, investigated by NREL¹⁴ and others, have high mobilities (>50 cm²/V-sec) and very low absorption in the visible. It was stressed by several attendees that high mobilities are crucial for a TCO to achieve a high figure of merit. Without high mobilities, the only way to achieve low resistance is higher doping or thicker films which both lead to larger free carrier absorption losses. Mobilities of Cd₂SnO₄ and CdIn₂O₄ increase with post-deposition anneals in O₂. Drawbacks to the presently-deposited cadmium oxide based films include use of toxic (Cd) and rare (In) metals and the need for annealing above 500°C. In addition, plasma “hardness” is a critical issue for a-Si applications, and 20-year thermal and chemical stability is required for any PV application. Any new TCO material must overcome these limitations and satisfy these demands. However, the potential and possibility of improved TCO’s has been established. Future fundamental work at the university level might build on the proof-of-concept established with these new TCO materials

to investigate related classes of materials or different deposition pathways to find a TCO with improved properties, which is also acceptable for large area, low-cost manufacturing.

It was pointed out that the textile industry routinely gathers outdoor exposure data that might be relevant to screening laminates and encapsulants. UV exposure standards for automobile fabrics and textiles from ASTM might be applicable to PV materials.

CONCLUSION

Several areas related to contacts and substrates have been identified where university-scale research can assist the transition of thin film PV modules from laboratory to manufacturing. Universities can develop or improve the characterization and understanding of TCO materials, in addition to pursuing several alternative TCO materials which have received little attention. In particular, interaction between the TCO and other semiconductor layers seems to limit application of some materials. Barrier heights and contact resistance between TCO and semiconductors should be investigated for several material systems. The performance of diffusion barriers between glass, stainless steel, or plastic substrates needs to be evaluated and new barriers should be developed if needed. Finally, universities can apply existing methods or develop new ones for characterization of module failure or degradation related to interconnection and shunting. These could either be integrated as a diagnostic on-line at the manufacturing plant or performed off-line on modules provided by industry. This is attractive for universities since the measurement hardware consists of generally available electronics and light sources.

REFERENCES

1. F. Willing, S. Wiedeman, J. Newton, J. O'Dowd and K. Jansen, 'Power optimization for large area a-Si solar modules,' *Proc. 21st IEEE Photovoltaic Spec. Conf.*, Kissimmee, FL, 1990, p. 1432.
2. J. Yang, United Solar Systems Corp., private communication, May 1997.
3. S. Albright, Golden Photon Inc., presented at this workshop, May 1997.
4. R. Gay, Siemens Solar Inc., paper to be published in this special issue.
5. S. Hegedus, H. Liang and R. Gordon, 'Transparent conducting oxides for amorphous silicon solar cells,' *Amer. Inst. Phys. Conf. Proc.* **353**, Lakewood, CO, 1996, p. 465.
6. S. Hegedus, W. Buchanan, X. Liu and R. Gordon, 'Effect of textured tin oxide and zinc oxide substrates on current generation in a-Si solar cells,' *Proc. 25th IEEE Photovoltaic Spec. Conf.*, Washington, DC, 1996, p. 1129.
7. T. McMahon, T. Basso and S. Rummel 'Cell shunt resistance and photovoltaic module performance,' *Proc. 25th IEEE Photovoltaic Spec. Conf.*, Washington, DC, 1996, p. 1291.
8. I. Eisgruber and J. Sites, 'Extraction of individual cell photocurrents and shunt resistances in encapsulated modules using large scale laser scanning,' *Prog. in Photovoltaics* **4**, 63 (1996).
9. A. Delahoy and A. Payne. 'Determination of the internal series resistance of CIS and CIGS photovoltaic cell structures,' *Proc. 25th IEEE Photovoltaic Spec. Conf.*, Washington, DC, 1996, p. 841.
10. W. Shafarman and J. Phillips, 'Direct current voltage measurements of the Mo/CuInSe₂ contact on operating solar cells,' *Proc. 25th IEEE Photovoltaic Spec. Conf.*, Washington, DC, 1996, p. 917.

11. J. Kessler, S. Wiedeman, L. Russell, J. Fogleboch, S. Skibo, R. Arya and D. Carlson, 'Front contact optimization for CuInGaSe₂ submodules,' *Proc. 25th IEEE Photovoltaic Spec. Conf.*, Washington, DC, 1996, p. 885.
12. R. Gordon, 'Preparation and properties of transparent conductors,' *Mat. Res. Soc. Symp. Proc.* **426**, San Francisco, CA, 1996, p. 419.
13. S. Wiedeman, J. Kessler, L. Russell, J. Fogleboch, S. Skibo and R. Arya, 'Progress in thin film CIGS modules,' presented at *the 14th NREL PV Review Meeting*, Lakewood, CO, Nov. 1996, to be published by *Amer. Inst. Phys.*
14. T. Coutts, X. Wu and W. Mulligan, 'High performance transparent conductive films of Cadmium Indate prepared by rf sputtering,' *Mat. Res. Soc. Symp.* , **426**, San Francisco, CA, 1996, p. 479.