Workshop: Device and Materials Characterization in Manufacturing

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SUMMARY

Diagnostic measurements of thin film materials and complete devices and solar modules are necessary to optimize both the processes and the resulting modules. Measurements provide the connection between processing and performance. In this workshop, the panel and audience examined both *in situ* and post-processing diagnostic measurements and how they can be utilized in a manufacturing environment to monitor processes and performance. The need for future measurement technology is increasingly for on-site, manufacturing-compatible, non-contact techniques giving rapid feedback in the production environment.

INTRODUCTION

Characterization has been essential to the advancement and realization of the photovoltaic technology.[1-3] Advances in this technology are due to an ensemble of creative contributions, including thinking, planning, realization, evaluation, and verification. Theory, materials science, processing, device development, modeling, testing, and measurement are co-dependent. None of these areas can stand alone; together, they provide for the successes and future of the technology. This paper highlights the evaluation and verification aspects of photovoltaics, with the objective of surveying the breadth of the characterization techniques. Table I presents a summary of current techniques, covering a wide-range of materials (composition, chemistry, and structure) and device (electro-optical, performance, and reliability) characterization methods.[4-6] An interactive workshop was held at the Thin Film Photovoltaic Symposium at the University of Delaware on May 1, 1997. The workshop on the topic, “Device and Materials Characterization in Manufacturing,” was lead by Jim Phillips of IEC. Panel members and their topics were: Jim Sites (Colorado State University) who discussed optical and electrical characterization of

CdTe ad CITS solar cells; Jim Rand (AstroPower) who described the need for materials and device diagnostics applied to thin Si solar cells; Larry Kazmerski (NREL) who presented the broad array of materials and device characterization available at NREL's centralized facility; and Jim Phillips (IEC) who discussed analysis of measured JV data to extract device and junction parameters. The key issues outlined by each panelist is given below.

MATERIALS AND DEVICE ANALYSIS: CENTRAL FACILITIES

Support for the U.S. National PV Program has been provided through a number of resources, including centralized facilities at national laboratories and universities. The investment in the test, measurement, and characterization facilities by DOE at the National Laboratories has been substantial.[7,8] These support operations were among the earliest investments by the National PV Program, with origins in the late 1970s.[8] The arguments for the establishment of centralized analytical support functions include economics (investment in major capital equipment to effectively serve the entire program), complementary diverse techniques at a single location (to address and unambiguously provide solutions to problems), a centralized expertise and information archive (for cross fertilization and as a repository for related technology issues), and the establishment of a independent source for standard evaluation of photovoltaic product. It should also be noted that the economics of the centralization of major facilities goes beyond the capital investment. Confining the operation of the instrument to a limited number of operators helps minimize maintenance problems and ensures consistency and correctness in data acquisition. Even under the best control, maintenance costs for such major facilities annually runs 7-10% of the equipment cost. There have been clear correlations between the number of operators and the increased cost of maintenance, downtime, and error. In general, the more sophisticated and specialized the technique, the more critical is the attention to controlling the number of operators.

These centralized facilities have traditionally offered multiple techniques for the microscopic and macroscopic evaluation of components. The range, illustrated in Table 1, provide vital information on the chemical, compositional, structural, electrical, and optical properties of surface and intramaterial features, as well at the performance properties of the devices.[9] Special strengths include the ability to link nanoscale spectroscopic events with the operation of large-area devices.

Two critical aspects of a central characterization facility are providing standardized measurements and developing new techniques. Regarding standardization, such laboratory facilities offer independent verification of performance for solar cell materials, as well as a repository for development of standard techniques, reference cells and materials, and for intercomparisons among research and industrial organizations.[10,11] Primary among such services has been in the area of cell and module performance evaluation (efficiency, power, etc.). Over the past 15 years, these efforts have developed standard procedures, measurement parameters, and references for these measurements. Moreover, those involved in these measurements have enhanced the precision of the techniques (e.g., see Table 2) and transferred them throughout the photovoltaics community. Standard evaluation of components has permitted the fair evaluation of product, the intercomparison of technologies, and provided the technical basis for fair competition worldwide. Most photovoltaic research and industry labs can trace their own measurements to one of the world's centers concerned with such standard characterization.[12]

Regarding development of new characterization techniques, it is extremely important to support the photovoltaic technology with state-of-the-art measurement capabilities—including those that are developed specifically for that technology. An example of one such method, which has leveraged its development with use in other semiconductor electronic applications, is the minority-carrier lifetime spectrometer developed by Ahrenkiel.[13] The system, shown schematically in Fig. 1, provides a non-contact and non-destructive means of evaluating the most fundamental measure of the quality of a semiconductor for use in a solar cell—the lifetime of the minority electrons and holes.[14] The technique is extremely versatile, as illustrate by the data shown in Fig. 2. It can accurately determine the lifetimes in direct and indirect bandgap semiconductors, bulk and large-area materials and sub-micron thick films, for single crystals and polycrystalline semiconductors, and for bandgaps covering the range from about 0.5 to more than 3.0 eV. This versatility certainly has application in PV manufacturing and research settings that deal with a variety of semiconductor products. Additionally, the technique can also be adapted directly into the manufacturing line (see following sections) to provide material evaluation and quality control before or following device processing. Such developments provide a important link, contribution, and technology transfer from the university or research lab to the manufacturing environment.

DEVICE DIAGNOSTICS

A logical question for solar-cell manufacturers is what type of device characterization can one set up that is relatively straightforward and gives answers at least by the end of the day. These criteria exclude some very useful characterization techniques that require trained specialists or are inherently time consuming. They include, however, significantly more characterization techniques and procedures that are in common usage. Some examples follow:

Optics. A low-end spectrophotometer with an integrating sphere can easily identify by wavelength optical losses due to reflection and absorption. It is particularly useful to make measurements after each layer of the fabrication process to associate the optical losses with specific layers and interfaces.

Full Photon Accounting. A combination of quantum efficiency measurement, using either a set of filters or an inexpensive monochrometer, and the optics measurement can generally account for all the photon losses in a reasonably well-behaved cell. These losses can be quantified by multiplication with the appropriate spectrum and integration.

Bandgap. The quantum-efficiency data can be used to determine the effective bandgap of the cell. The best procedure is to compare the long wavelength cutoff with that of a known bandgap cell. Such determination is particularly useful when using an alloy absorber or when interdiffusion between window and absorber layers is suspected.

Resistive Losses. Resistive losses can be relatively easily quantified by analysis of current-voltage curves. One technique for series resistance is to plot dV/dJ vs. $(J+J_L)^{-1}$ and extrapolate to zero inverse current. Quite commonly, both series and shunt resistances will be smaller in light than in dark. The light values can easily be translated to an efficiency loss.

Junction Quality. A reduced-quality diode junction is commonly the result of extraneous forward-current recombination. A logarithmic plot of forward current vs. voltage, preferably after resistive correction and preferably in contrast to an ideal junction, will reveal the diode quality factor from the inverse slope, the excessive recombination current, and the impact on operating voltage.

Anomalous Effects. There are a number of anomalous solar-cell effects that are not easily analyzed in detail, but are nevertheless identified as problems through qualitative examination of current-voltage curves. These include cell non-uniformities, transient response, band offsets, contact barriers, illumination modification, and voltage modifications.

MANUFACTURING EVALUATIONS: CURRENT AND PROJECTED NEEDS

Industry cannot wait. Rapid response, pertinent information, immediacy, and problem identification and solution are paramount to product evolution and market competition. The traditional approach has been to use centralized facilities for sophisticated and more costly measurement requirements, and for confirmation of milestones and to ensure compatibility in the standard performance areas. Currently, there is a growing activity in the development of manufacturing-environment measurements, primarily *non-contact* techniques that are incorporated on-site and perhaps directly into the manufacturing line to monitor and ensure product quality. These techniques range from fundamental property determinations through current-voltage spectroscopies, and represent a growing area of need and investment for the PV industry. Finally, as the industry diversifies (i.e., having multiple PV products under a single ownership), the versatility of the measurement technique becomes important. The availability of a specific method for thin films and bulk crystalline materials, for low bandgap absorbers and wide-bandgap windows, for sub-mm^2 as well as cm^2-areas is desirable.

Some examples of industry needs in the thin-film materials and device areas are represented in the following sections. Also, some indications of future directions for industry-required characterization and methodologies are presented.

Industry developing techniques for thin films

The characterization needs of industry fall into two general categories: characterization needed to insure product quality, and that needed to increase performance (through enhanced device and material understanding). An example of the former is resistivity measurements on grown films where the measurements are made on a regular basis in the manufacturing line. Feedback is provided to the operators of the deposition systems and actions can be taken based on the results. An example of the measurements needed to increase performance is spectral response. A spectral response can help understand strategic performance limits such as blue response and effective diffusion length in silicon based solar cells. Using such a tool to provide feedback to the film growth effort would be untenable due the need for a finished device, limited area measured, and complexity of the measurement.

Rapid-turnaround testing carried out in the manufacturing line is of the most immediate need in industry. Optimally, such a measurement is contactless, requires no device preparation, is non-destructive, is not subject to detailed interpretation, and is predictive of final device performance. Alternately, the tools needed to characterize finished devices for potential improvement are well in hand in the industry already.

The measurement of minority carrier properties (as mentioned earlier) is an active area of development for in-line quality control. Application specific development is needed for this tool. For silicon, minority carrier properties can be important in silicon ingots, sawn wafers, free-standing grown sheets, and deposited films. The presence of grain boundaries poses a second variable. RFPCD measurements on polycrystalline silicon wafers can not be interpreted in the same fashion as those measurements on single crystal silicon. There is some questions whether such measurements taken on polycrystalline silicon with a high density of grain boundaries is predictive of device performance at all. Monitoring of shunts in large area deposited films is another area for in-line measurement development. Measurements like these are in need of further research and development to become fully integrated in the manufacturing environment.

Electronic interactions

The cost of capital investment in major analytical services has been met by the establishment of centralized facilities to serve the entire program (see above). The dissemination of results is enhanced through the evolving avenues of electronic communications. Currently, direct transfer of data from the instrument to the client is utilized extensively.[8] The evolution of the worldwide web (www) has provided the ability for the client to access data in real time and archive it for future use. The constraints/requirements for proprietary information essential for industry competitiveness have led to the development of protected mechanisms for storing and transferring critical measurement information. This has not only enhanced the speed of information transfer, but has provided the first paths for direct presence of the customer into the remote laboratory. This has led to increased interactions between the person who best knows the problem and the person doing the analysis—benefiting the efficiency, time, and value of the diagnostic operation.

As these electronic communications are further implemented into the analytical capacities, other options are becoming viable. Currently, characterization scientists can operate and access even sophisticated analytical systems remotely (e.g., from their office or from a travel location). This is being extended to providing true user facilities; operated by the client at the remote industrial site. Certain routine measurement and test systems should be expected to accessible by the remote client within a few years.

SUMMARY AND RECOMMENDATIONS

The requirements and trends for characterization to assist the phototovoltaic manufacturing industry can be defined in several areas:

- *Rapid response*. The ability to access data in the shortest possible time is critical to the manufacturer. Central analytical facilities and universities have to work with industry to ensure that the analysis is performed in a time reasonable to the manufacturer client; prioritization and communication are key to ensuring responsiveness.
- *Interpretation and information.* The primary interaction and output metric between the characterization scientist/engineer and the client is the interpretation. Of course, the interpretation depends upon a number of factors from applying the correct technique (analysis end) to the information on the sample (client end). Proper interpretation is important. There is a growing realization that simplicity and trend recognition (not detail and complexity) are the measurement areas that provide quality control.
- *Technique versatility*. With the increasing trend in product diversity (e.g., single-crystal and polycrystalline thin-film cells) for a single manufacturer, the ability to use a given technique for a variety of device types is desirable. Of equal importance, the capability to perform non-destructive, non-contact measurements greatly enhances importance of the technique for rapidity of analysis and more implementation directly into the manufacturing line. This is one area where universities can contribute to improved characterization methods.
- *Research and technique development.* The demands of the industry continue to expand with the diversity of the product. These demands require research into measurement science and the development of new measurement techniques aimed specifically at the PV technology. These requirements range from the

analytical aspects of data interpretation, through alteration of standard techniques for PV application, to the development of new characterization methods to meet the needs of the manufacturing environment. Technique development covers the regime from large area for modules to nanoscale technologies for diagnostic evaluations; from determination of rapid events such as pico- and femtosecond lifetimes to longer-term reliability testing; from more precise measurements of performance through routine evaluations for classification of product. Measurement needs and capabilities are expanding with the technology.

- *Manufacturing-environment measurements*. The needs for the industry are not only directed for immediate analysis, but also for the incorporation of techniques at the manufacturing site. Of special interest and application are non-destructive, non-contact test and measurement techniques that can be incorporated directly into the manufacturing line to ensure the quality of the photovoltaic material/product. This is currently an area of growing interest, and one that demands the collaboration of the DOE Program’s assets at universities and national laboratories with the industry.

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FIGURE CAPTIONS

Figure 1. Schematic diagram of minority-carrier lifetime spectrometer.

Figure 2. Data from lifetime spectrometer from several different semiconductors. The lifetimes are obtained from the linear fit as indicated.