INFORMATION TECHNOLOGY STRATEGIES FOR THE PRODUCTION OF SOLAR CELLS

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ABSTRACT

Solar cells are photovoltaic devices made up of different layers of materials: substrates, semiconductors, dielectrics, metals, transparent conducting oxides (TCOs), anti-reflection coatings, encapsulants, etc. Each layer serves a particular role in the overall functioning of the device. In these structures, the semiconductor layers serve the purpose of converting solar photons to electron-hole pairs and establishing the electric field necessary to separate charge and generate external power. Different cell technologies are known primarily by which semiconductor(s) performs this task.

As with most manufacturing processes, information technology is playing an ever-increasing role in the production of solar cells. Currently, NREL's polycrystalline thin film group uses a client-server architecture for collecting data from both measurement-test apparatus and prototype manufacturing equipment. Data from these machines is transferred to a central data warehouse where analytical and data mining techniques are used to study both existing and yet unknown correlations between solar cell fabrication and performance/stability metrics. In an effort to facilitate data exchange with future systems we are developing an information technology strategy based upon the CAMX (Computer Aided Manufacturing using XML) standards to facilitate the efficient transfer of data between data publishers and consumers. By making use of CAMX, we feel that it can greatly reduce the cost and effort of exchanging information and will allow us to focus more resources on our core mission.

INTRODUCTION

NREL's current information system for polycrystalline thin film device fabrication can be described in regard to three primary functions: 1) client-server architecture, 2) data warehousing, and 3) data analysis.

Client-Server Architecture

A key component of any information system is how data servers (publishers) interact with data clients (consumers). In rudimentary designs, isolated databases are located on individual computers near key process and characterization steps. These data "islands" serve only as data repositories and do not represent true integrated information systems. In our current design, computers located at various process and measurement-related stations log key elements associated with device processing and performance and stability measurements. These data publishers are connected via Ethernet to a central database that consists of numerous tables, each of which encapsulates data specific to the particular station.

Data is generated at each station in a variety of formats. Custom-written interfaces are commonly written to generate these text-based files. For example, our current density-voltage (J-V) measurements (used to monitor both initial as well as stressed device performance) are obtained using Labview code that generates output text data in a header-column format. Header lines contain information about the measurement (device identifiers, date/time stamps, measurement temperature) while columns contain the raw J-V data. Some data is collected from older legacy applications that log their data in proprietary database formats like DB3. Open database connectivity (ODBC) drivers are used to automatically upload parsed data from raw data files to a central database.

A key disadvantage of this technique is the high degree of customization inherent in such an approach. The lack of standardized data formats requires considerable programming each time a new data publisher or consumer is added to the system. For this reason, we are investigating the use of CAMX as a data schema capable of providing a common method to exchange information among entities in an environment encouraging code and technique reuse.

CAMX makes use of predefined xml (Extended Markup Language) messages for encapsulating data and a message broker for exchanging the messages. The syntax and semantics of the xml messages are defined by xml schemas which have been documented in the CAMX standards. CAMX also defines a common protocol for exchanging xml messages using a message broker. The message broker uses widely accepted internet protocols such as XML, HTTP and SOAP that are programming language and operating system agnostic. This will allow us to build a consistent infrastructure that is flexible both within and outside of its current scope.

Data Warehousing

The data warehouse serves as the principal location of all relational data associated with how the solar cell is made as well as measurements and characterization studies performed on that device. Tables or entities in our current database use an entity-relationship diagram (ERD) from which a star schema similar to that shown in Figure 1 can be generated. Each record in the Device table therefore represents a "fact" which correlates a time-dependent snapshot of performance linked with different processes (Proc) and characterization (Char) entities. This data structure defines a sound approach for the dimensional modeling of device performance and reliability with device fabrication history[1].

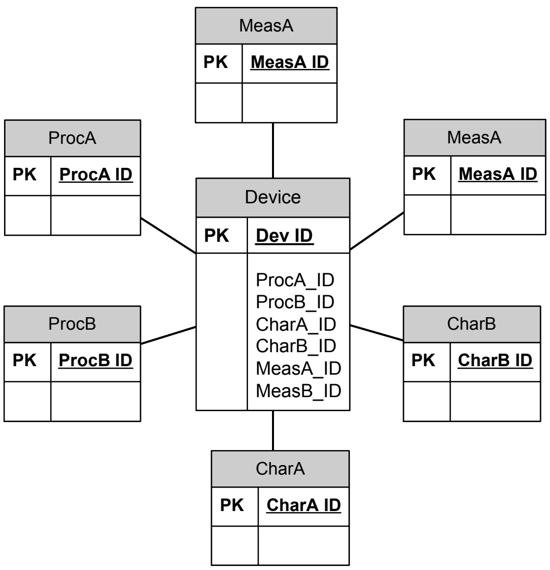

Fig. 1. Star schema used to model device performance as a function of characterization and fabrication.

Characterization entities include various analytical measurements made during and after a device is fabricated. These measurements provide the data necessary for understanding the "science" of the process. Measurement techniques include those that focus on the electrical, optical, and chemical nature of the device at a particular time during its fabrication. Correlating the "state" of a device before and after a particular process by taking "snapshots" of such data is the common technique for establishing the impact of that process.

The data warehouse uses table ERDs capable of supporting the star schema shown in Figure 1. For fabrication processes in which the sequence of layers, growth techniques, and even materials are not fixed, the ERD must also be flexible. Fortunately, all device fabrication schemes can be derived from the common ERD design pattern shown in Figure 2. This diagram supports the logic that all devices can be represented by one or more layers of one or more materials deposited by one or more processes with no constraints regarding how the individual layers are combined.

Since CAMX was initially developed for the electronics industry, significant effort went into developing xml data structures that can transmit data from the variety of testers used in electronics manufacturing. These data structure will be very helpful in transferring information from test and fabrication equipment located at NREL to the appropriate databases. This approach can also be used to facilitate communication between separate data warehouses, so data mining can be conducted across all repositories of information.

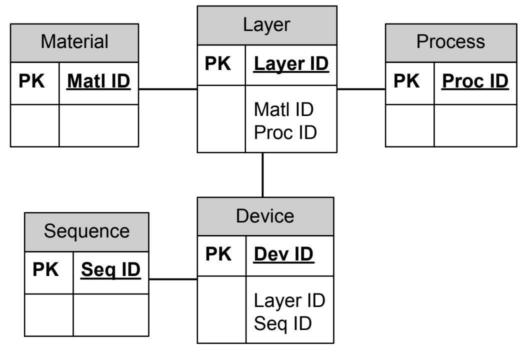

Fig 2. ERD design pattern common to all solar cell fabrication processes.

Data Analysis

Data can be extracted from our data warehouse to networked clients in many ways. Subsets of data can be defined by standard sort-find operations and then downloaded using simple scripts in .csv and .txt formats for importing into other graphic or display applications. For more advanced analysis, we have adopted the use of JMP (SAS, Inc) statistical software for providing analysis features far beyond simple graph generation. In addition to providing capabilities for data modeling and visualization, JMP also provides a strong design of experiment (DOE) front-end for designing efficient experiments. Being a true database product, JMP also features an ODBC interface for importing datasets using structured query language (SQL) scripts. These scripts can be saved and re-used as necessary.

Data analysis can involve analyzing both large datasets (e.g., collected from many experiments performed over long periods of time) as well as much smaller sets, typically defined within the context of a given "experiment". The latter, more selective datasets, if properly designed from the onset, can be used to generate orthogonal models correlating dependent responses, like efficiency or stability, with various factors studied in the design (temperatures, times, thickness, etc.). These models generally are well correlated with actual results.

EXPERIMENTAL RESULTS

Examples of analysis in which data extends over experimental boundaries are numerous. Process control charts in which the performance of identically processed devices is monitored over time are a good example of this type of analysis. One actual analysis performed involved comparing the performance of devices as a function of substrate positioning. For CdTe devices, a single CdTe deposition is performed on a 1.5" x 1.5" substrate which is further reduced to a device substrate size of 0.75" x 0.75" upon which we define two individual devices. Due to the spherical symmetry associated with transporting CdTe to the substrates, devices located more towards the center of the substrate (labeled "1") were expected to be slightly thicker than those devices (labeled "2") located on the substrate perimeter. A one-way analysis of variance (ANOVA) test was performed to compare the performance of "1" devices relative to "2" devices. The heights of the diamonds shown in Figure 3 are representative of the 95% confidence intervals for the means of these two populations shown as individual data points. The horizontal line within each diamond is the respective population mean while the horizontal dashed line is the overall mean. As can be seen in Figure 3, even though the mean performance of the "1" devices is indeed slightly larger than the mean of the "2" devices, statistically, the two groups are not different, and thickness effects can be safely ignored when treating "1" and "2" devices as identical.

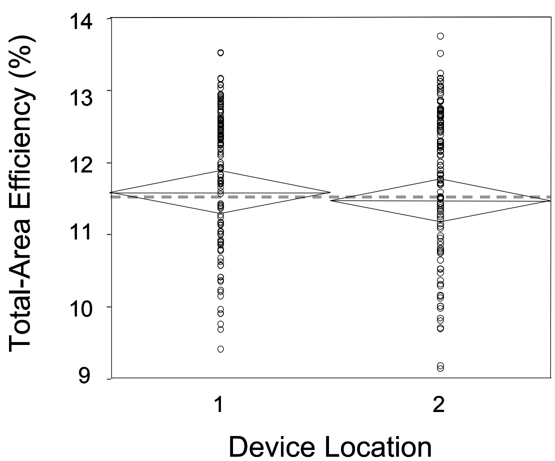

Fig. 3. ANOVA test to determine whether devices located towards the substrate center (1) are different relative to devices located at the perimeters (2).

Another example of how an analysis might involve several experiments is when comparing different device fabrication procedures or "technologies". Device stability is currently monitored by measuring the performance of a device as a function of time under which it undergoes stress testing. Figure 4 shows the same 95% confidence interval diamond figures for the %change in open-circuit voltage, V_{oc}, measured in several different types of $CuInGaSe_2$ and CdTe polycrystalline devices after 520 hrs of stress testing under 1-Sun illumination at 85 °C and non-biased conditions. In this figure, the letters A through G represent different ways in which the devices were made. The horizontal dashed line represents a zero percent change. From this figure, it is readily apparent that intrinsic stability varies according to device technology. While some devices show little and even slight improvements with stress (B, C and E), other technologies are significantly less stable (D, F, and G).

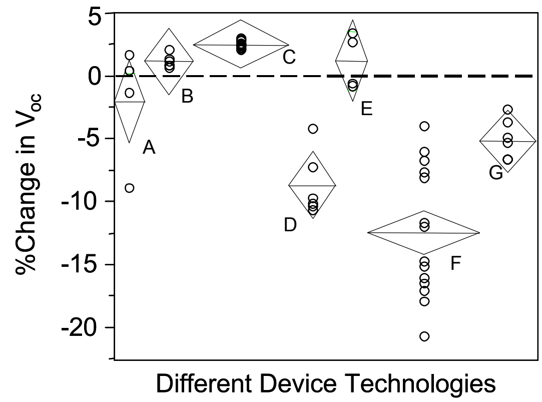

Figure. 4. Stability shown as the %change in V_{oc} observed in different technologies after 520 hrs of V_{oc} – 1 Sun – 85C stress testing.

Experiments that use DOE methods for designing experiments correlating several processing variables (factors) with performance and stability responses can be used for generating empirical models for process optimization. In one such study[2], a large 3x2x2x2 orthogonal experiment with 2 replicates (48 devices) was used to determine how performance and stability was affected when the CdS and CdTe film thickness was varied between 60 to 100 nm and 8 to 11 microns respectively. This study also involved determining the effects of nitric-phosphoric (NP) acid as a pre-contact etch and oxygen as an additive to the vapor $CdCl_2$ (VCC) process. Multiple linear regression models for V_{oc}, short-circuit current density (J_{sc}), fill-factor (%FF), and efficiency (η%) after initial fabrication and after stress testing were generated from these orthogonal designs and subsequently compared with actual data using simple residual analysis. Regression models for unstressed devices were extremely well correlated with actual performance data. Figure 5 shows the correlation between actual and predicted device V_{oc} for unstressed devices using one such regression model.

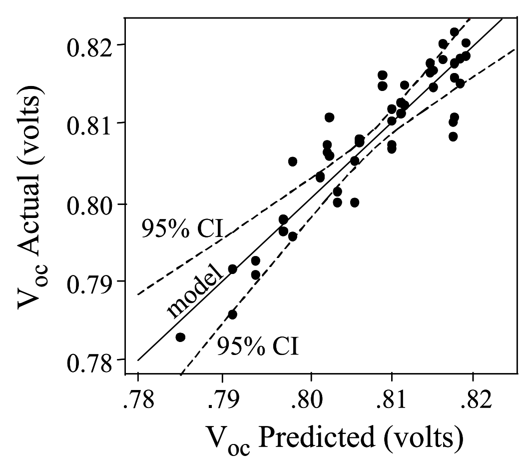

Fig. 5. Actual device V_{oc} vs. model predicted V_{oc} for initial device performance.

One of the primary advantages of generating a well-correlated numerical model is the ease at which it facilitates optimization of performance and stability as a function of processing. JMP provides several interfaces for response optimization within multi-dimensional process spaces. One of these is the use of contour plots in which the user can monitor output responses as a function of two different variables. Figure 6 shows contour plots for the %change in measured device efficiency after 700 hrs of stress testing. In this experiment, device stressing consisted of exposing devices to 1-sun illumination while heating them to 100 °C. As in the previous studies, device bias was not intentionally controlled.

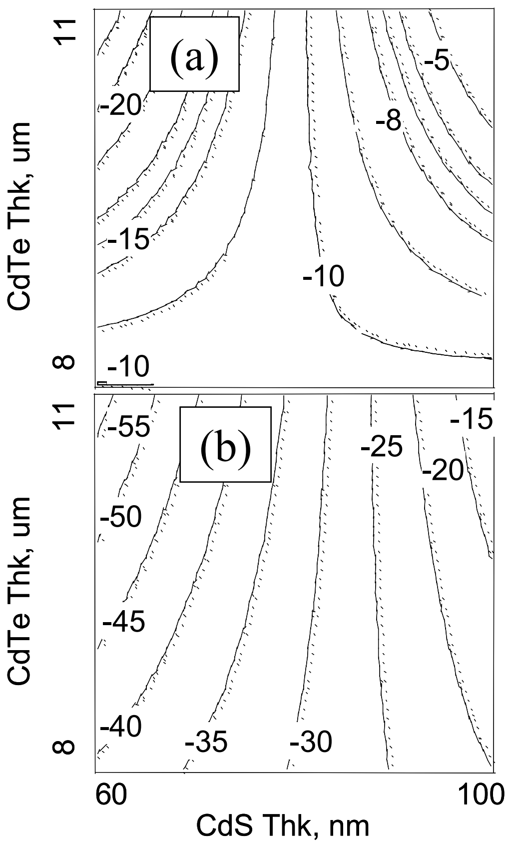

Fig. 6. Contour plots of the %Efficiency decrease observed after stress testing (700 hrs) devices annealed with (a) and (b) without oxygen during the vapor $CdCl_2$ step.

The contour plots shown in Figure 6 differ by whether oxygen is present (a) or absent (b) during the VCC process. These figures show models generated for devices where NP etch was used prior to backcontact processing. It is quite obvious that having oxygen present reduces the overall degradation observed in these devices. Film thickness also appears to have a strong effect on stability. Thicker CdTe and CdS films are obviously better for stability.

CONCLUDING REMARKS

An information system for managing polycrystalline solar cell device fabrication, characterization, and performance data has been implemented at NREL. This system uses a client-server architecture in which automation is used to minimize data-entry overhead. Data is stored in a central data warehouse which is accessible to clients via an ethernet network. Data analysis involves downloading sets of data from the central data warehouse to client computers. For advanced data analysis, JMP is used to both design statistically sound experiments as well as perform modeling between performance and stability responses as a function of device processing. In order to reduce the resources required to extend and maintain this architecture, NREL and the Georgia Institute of Technology are working collaboratively to implement a data collection and distribution system based upon XML and a schema defined by CAMX. CAMX offers a standards based approach for the exchange of information among data producers and consumers. It makes use of widely accepted internet protocols which are supported by a variety of operating systems and programming languages.

Since CAMX was developed to exchange information on the electronics manufacturing factor floor, there are great opportunities to use CAMX throughout the solar cell manufacturing industry. By demonstrating the benefits of CAMX at NREL, the jump to implementation in industry and the corresponding cost reductions should be realized more quickly.

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