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Nondestructive Performance Characterization Techniques for Module Reliability

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Nondestructive Performance Characterization Techniques for Module Reliability

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ABSTRACT

This paper describes nondestructive characterization techniques for module reliability. These techniques include light and dark current *versus* voltage and related analysis such as resistance, diode quality factor, and dark current. The use of the NREL laser scanner at zero volts and forward bias is also described as a technique to uncover cracks, shunts, and open-circuit regions in a module. Quantum-efficiency measurements of isolated cells or regions in a module are also possible. The interpretation of laser-scanning data is enhanced by hot-spot testing with an infrared camera or thermographic paper. Specialized nondestructive techniques have also been developed to determine the shunt resistance of individual cells in a module by selective shading of cells under sunlight. Ultraviolet fluorescence and reflectivity measurements at NREL have proven useful in evaluating encapsulant stability.

1. Introduction

When modules or systems change their performance in the field it is often desirable to determine why in a nondestructive manner so that the samples can be redeployed to monitor further changes. This paper summarizes the nondestructive analysis capability within the National Center for Photovoltaics at NREL, with emphasis on the capabilities of the PV Cell and Module Performance Characterization team. These capabilities include current *versus* voltage (I-V), quantum efficiency, laser scanning, shunt-resistance screening, hot-spot testing, and reflectivity / fluorescence analysis. This paper will not discuss reflectance and fluorescence as a tool do determine the state of degradation of encapsulants but a summary of the technique can be found in [1,2]. Visual inspection of the module is essential to identify delamination, corrosion, cracks, electromigration and other exposure related defects.

2. Current *versus* Voltage

The most common procedure to determine performance changes is to measure the I-V properties under standard illumination and determine if the maximum power has changed. Unfortunately, the maximum power has relatively large random error, which hampers the ability to resolve changes. At best, this random error in the maximum power is typically ±2%. If the modules are mounted in a system, then it is time consuming to individually unmount the modules, bring them inside, and test them. An alternative is to determine the performance of the system as a function of time. The method developed at PVUSA bases the power on a multiple linear regression of power as a function of air temperature, plane of array irradiance, and wind speed [3]. This method can be used to determine the performance of a system over time in monthly chunks or any other time interval. Figure 1 is an example of the user interface of a Labview program that allows analysis of any testbed's data set(s) providing there is a text file that contains the data, time, plane-of-array irradiance, air temperature, and wind speed. This particular version handles data from 7 different systems and individual module testbeds. The program takes about 2 min to read in the data and about 10 s to process the 161,000 data points based upon user selected filtering via sliders in the example. There is no upper limit to the number of points that the software can analyze. It has analyzed more than 300,000 points for one system.

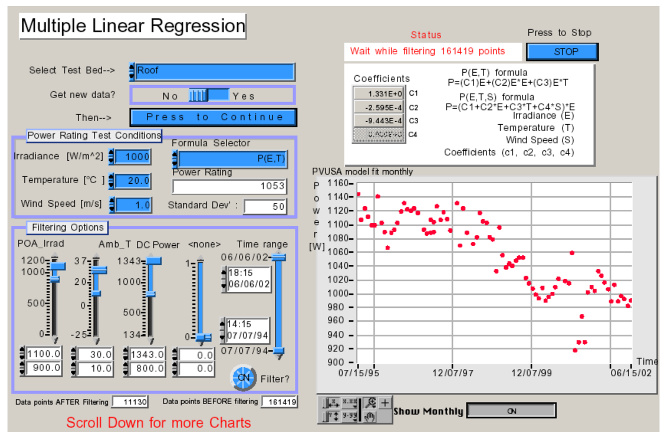

Figure 1. User interface for Labview software package to evaluate the maximum power using a multiple linear regression to irradiance, air temperature, and wind speed.

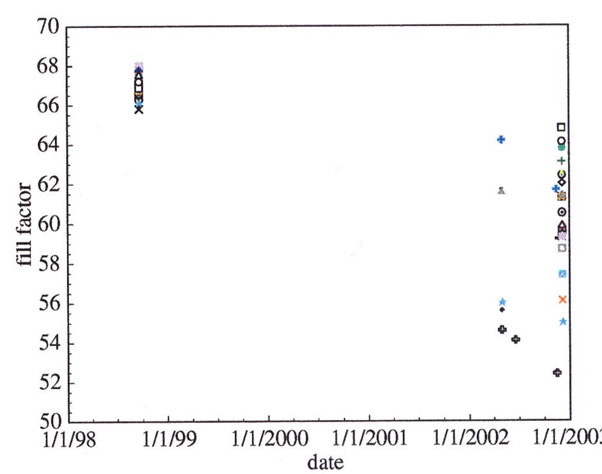

Figure 2. Fill factor changes with exposure time for 28 CIGS modules.

Other parameters such as fill factor are relatively insensitive to the error in setting the irradiance. Figure 2 shows the change in performance of 28 copper indium

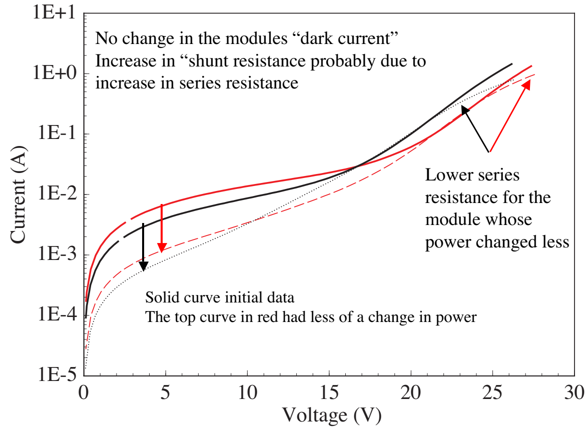

Figure 3. Dark current versus voltage for a module with a large change in power compared with a module showing a smaller change in power.

gallium diselenide (CIGS) modules as a function of time in the field. The change in fill factor, FF, is characterized by an average of the samples of 66.7% initially, with a standard deviation of 1.8%, and 60.3% recently, with a much larger, standard deviation of 5.3%. There was no significant change in the short-circuit current, I_{sc}, until recently, with a possible 5% decrease for some modules in the last 6 months. The change in the open-circuit voltage, V_{oc}, was negligible. To explain the decrease in FF the other I-V parameters were investigated. Figure 3 compares the dark I-V for a module with a small change in FF and one with a larger change. It appears that the fill factor changes cannot be explained by shunting because the low-voltage region actually decreases for both modules. It also appears that there is no measurable change in the portion of the curve where the log of the current is linear with voltage, indicating no appreciable change in the diode quality factor or dark current. The only significant difference is the high-voltage series-resistance region. The light I-V curves minus I_{sc} show similar behavior with more noise due to light-level fluctuations. The resistance at V_{oc} is linearly related to the series resistance in that the intercept of a plot of the resistance at V_{oc} versus $1/I_{sc}$ is the series resistance [4]. Figure 4 shows that there is a large change in the series resistance from the initial values and the present values and provides an explanation for the drop in power and fill factor.

3. Quantum Efficiency

The quantum efficiency of a single cell in a module can be measured and can provide insight as to why the short-circuit changed. Figure 5 shows the quantum efficiency of an exposed and unexposed mono-Si module [5]. The drop in the ultraviolet region can be explained by EVA browning [2]. However the drop in the infrared region cannot be explained by EVA transmission changes, but can be explained by a decrease in the diffusion length.

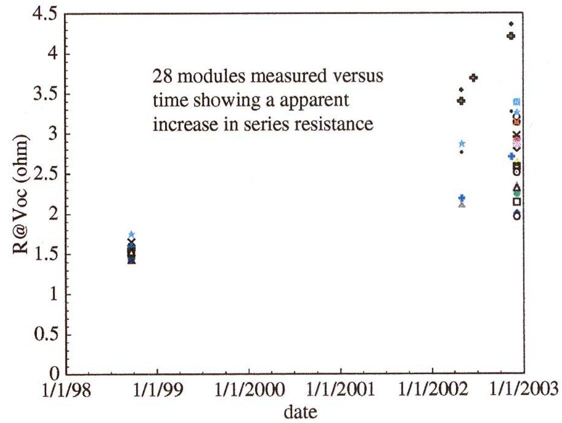

Figure 4. Changes in the resistance at V_{oc} for the modules in Fig. 1, showing a significant increase with the lower fill factors having the higher resistances.

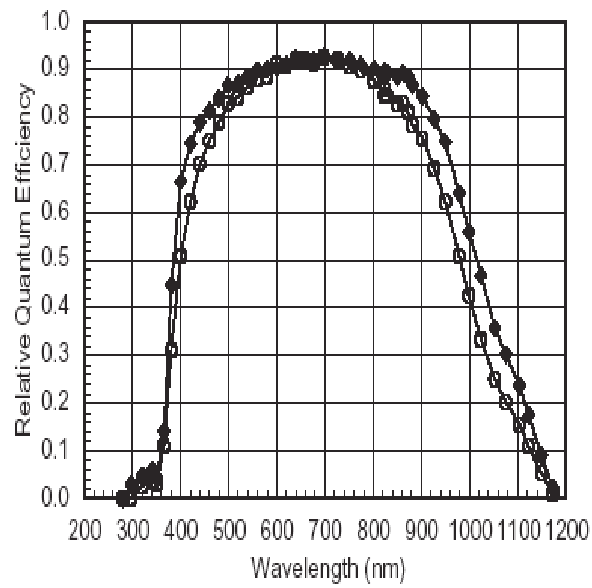

Figure 5. Changes in the quantum efficiency for a single cell in an unexposed module (diamond) and after exposure (circle) [5].

4. Hot-Spot

Modules in forward or reverse bias can exhibit hot-spot heating. There are international test procedures to determine if hot-spot heating is a problem [6,7]. Figure 6 is an example of a hot-spot of a mono-Si cell in a short-circuited module under one-sun illumination [8]. Localized heating can also occur in thin-film modules in forward bias because of resistance losses at the scribe-line interconnect region. Thin-film modules can be damaged by excessive reverse bias (voltages>V_{oc}), so testing is often carried out in forward bias. Hot-spot analysis can be conducted with an infrared camera or with temperature sensitive film in contact with the module surface. The temperature-sensitive film is inexpensive and sensitive to a few mm, but is translucent so it is normally used in the dark with the module in small reverse bias or in forward bias. Defects in a module related to high-resistance paths, localized shunting defects, or severely current-mismatched cells in a series string appear as hot-spots..

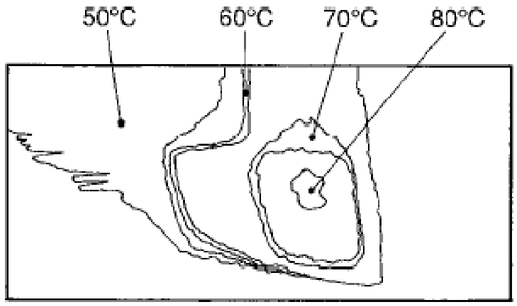

Figure 6. Thermogram of hot-spot heating of a mono-Si cell in a short-circuited module illuminated at one-sun [8].

5. Laser Scanning

Laser scanning as a function of bias voltage, wavelength, and chopping frequency can uncover a variety of problems in a module, including cracking, shunted cells, nonuniform current generation, high-resistance regions, and other information [9,10]. A laser scan of a multi-Si module at zero voltage bias showing multiple defects including open-circuited regions from cracks (black) and severely shunted cells (red), is shown in Fig. 7. This module was damaged as part of an attempt to mount cells on a solar race car.

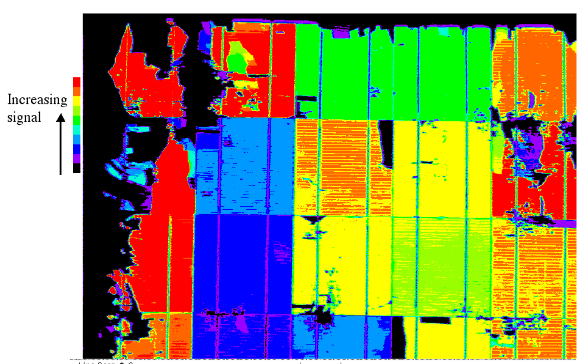

Figure 7. Damaged multi-Si module showing cracks and shunted cells.

It is often desirable to perform laser scanning on modules with less obvious defects, such as the modules shown in Fig. 8. Often more information can be obtained by performing a line scan across all the cells or along one cell. Figure 9 shows a line scan of the module in Fig. 8 across the cells near where the arrows are.

An alternative to laser scanning to identify shunted cells has been developed by McMahon and others [11]. This method is more accurate for cells that have light dependent shunts because the module is illuminated. Figure 10 shows an example of the technique from reference 11.

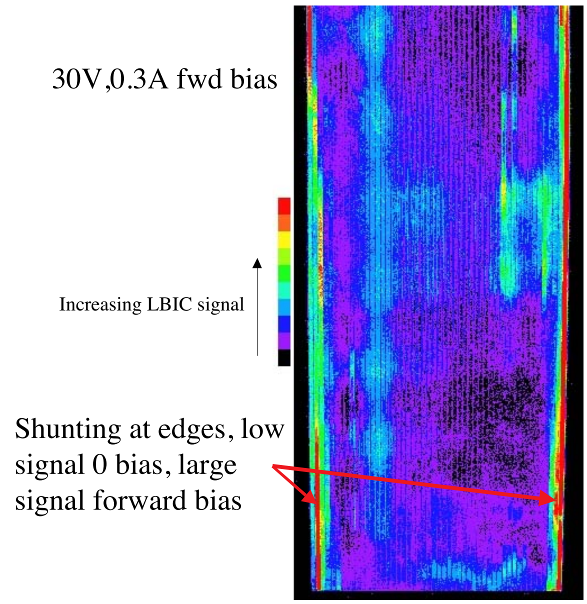

Figure 8. A laser scan of a thin-film module showing shunting at the edges.

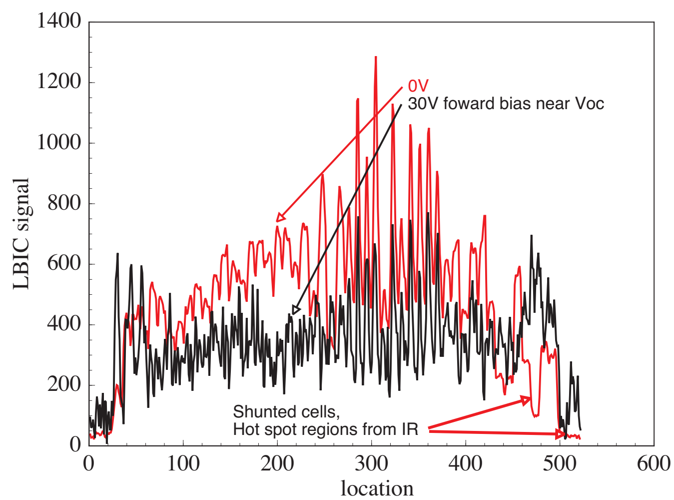

Figure 9. Line scan at two bias voltages near the bottom of the module in Fig. 8.

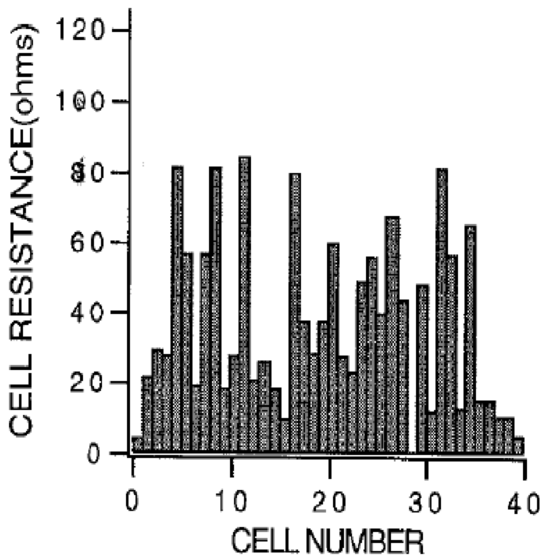

Figure 10. Shunt resistance of individual cells in a module [11].

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