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Introduction to Photovoltaics Failure Analysis and Reliability

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Section 1: Introduction

Photovoltaics (PV) are becoming an increasingly important solution to meet the demand for renewable energy. The rapid growth and adoption of this technology means that microelectronics failure analysis and reliability experts may be called upon to address current and future challenges. This article provides a brief primer on common failure mechanisms found in PV component devices, as well as the associated failure analysis techniques to identify them.

Section 2: Comparison of PV and Microelectronics Failure Analysis and Reliability

The failure analysts and reliability engineers in the PV industry must address challenges that their counterparts in microelectronics do not necessarily face. The key differences between the PV and microelectronics industry from a failure analysis and reliability perspective include:

1) Failure mechanisms dominated primarily by packaging issues over greater length scales;
2) Poorer process control;
3) Relative lack of detailed reliability data.

The overview of common PV failure mechanisms in this article largely consists of packaging-related issues. Therefore, while most microelectronics failure analysis techniques are applicable to PV devices and components, only a subset of tools are frequently utilized beyond product development. Furthermore, larger product dimensions result in higher costs to create defect localization tools and test chambers.

PV reliability analysts also face poorer process control. While PV manufacturing is increasingly automated, a greater number of manual steps remain compared to the microelectronics industry. To further complicate matters, system reliability is also contingent upon the quality of the installers, an aspect in which manufacturers have little control over.

Generating detailed reliability data for accurate lifetime prediction is difficult for the PV industry. While there are many PV modules in the field, these devices come in a variety of materials systems (*e.g.*

silicon, III-V, II-VI, *etc.*), configurations, and use conditions. PV systems have long expected lifetimes — the 25-year warranty is presently an industry standard, though there is no uniform definition for failure [1]. The discrepancy between expected lifetime and probable technology lifetime necessitates accelerated testing [2][3]. Long expected lifetimes mean that this accelerated testing can be especially expensive and time consuming.

Section 3: Overview PV Failure Mechanisms

This section highlights common failure mechanisms facing the PV industry [4], [5],[6]. Table 1 provides a summary of the failure mechanisms along with the relevant failure analysis technique for diagnosis. There are a number of failure mechanisms specific to certain PV materials systems and configurations that are not addressed in this article. This general overview article focuses on crystalline silicon PV, which still dominates the industry as of this writing.

Table 1: Common PV failure mechanisms and applicable failure analysis techniques

Failure Mechanism / Failure Analysis Technique	**IV Curves**	**Electroluminescence**	**IR Imaging**	**Visual Inspection**
Broken Interconnects	X	X		X
Broken Cells	X	X		X
Bypass Diodes / Hot Spots	X	X	X	
Corrosion	X	X		X
Delamination				X
Encapsulant Discoloration	X			X
Junction Box				X

<u>Broken interconnects</u> within the module occur due to thermomechanical stress caused by the outdoor operating environment of PV modules [4]. They were a common source of failure in early PV modules. Accelerated testing is crucial for evaluating a module design's robustness with respect to broken interconnects, since the performance impact develops over long time periods. This failure mechanism can be identified as dark regions in the electroluminescence image where the failed interconnect would otherwise be collecting carriers. Primary mitigation strategies center on decreasing thermal expansion coefficients of substrates and implementation of redundancy.

The outdoor elements such as hail storms can result in physical trauma leading to broken or cracked cells. Long term mechanical stress due to situations such as snow loading can also result in broken cells. The exact cause of a broken cell is difficult to determine after the fact. Its presence can be identified through electroluminescence followed by visual inspection. Packaging improvements, decreased module size, and screening for pre-stressed cells can lower the occurrence rate of this failure mechanism.

Failed bypass diodes can hinder the performance of PV modules. Bypass diodes are placed in parallel with PV cells in the opposite direction of the cells' p-n junctions. Their purpose is to dissipate the reverse bias current and voltage stress that otherwise occurs when a subset of cells are shaded or underperforming. Bypass diodes that fail short can be identified using electroluminescence. If the bypass diode fails open, the reverse bias stress from partial shading can lead to significant heat dissipation and the formation of hot spots [4]. These hot spots can be identified through IR imaging. Prolonged operation in this condition can result in further solder or backsheet damage or arc faults.

Interconnect corrosion results from delamination and subsequent moisture ingress [7]. The inherent voltages in the system can drive ions and further accelerate corrosion. The effects of interconnect corrosion can manifest in the form of decreased fill factor in the IV curve and further verified with electroluminescence or visual inspection [8]. Interconnect corrosion can cause arc faults, which lead to further damage and hazard. Encapsulant improvement has been the primary approach to minimizing this failure mechanism.

Delamination is a common defect for modules after extensive time in the field. By its own, delamination diminishes transmission and cell performance [4]. More importantly, delamination is a gateway to subsequent moisture ingress and corrosion of interconnects. It plays an especially important role in thin film photovoltaics where PV cell materials are susceptible to corrosion [5]. Visual inspection can often identify this failure mechanism.

Encapsulant discoloration is a primary cause of efficiency degradation, especially among early modules [4]. The primary purpose of the encapsulant, similar to that in microelectronics, is to protect the PV cell from moisture. Unlike microelectronics mold material, however, PV encapsulant experiences long-term exposure to ultraviolet light, which diminishes transmission. While not a cause of catastrophic failure, its role in diminishing cell performance over time attracted significant efforts to formulate improved encapsulant materials [8]. Visual inspection is used to make the final determination of whether or not discoloration has occurred.

Junction boxes reside on the back of the panel and provide the connection between the PV module cells and the PV system. Like the modules themselves, they are also susceptible to moisture ingress and corrosion [6]. Degradation in junction boxes is a matter of concern due to the higher potentials present when compared to an individual PV cell. Therefore, the risk of hazardous arc fault events is significant at the junction box.

The above failure mechanisms are either general to PV or specific to crystalline silicon modules. Due to the diverse configurations and materials systems in PV, however, there are many specific failure mechanisms that are worth mentioning. For example, while concentrating PV promises higher efficiencies, the additional complexity of tracking the sun and focusing its irradiance comes with susceptibility to additional points of failure. Such failure mechanisms include mechanical failure of the tracker and degradation of the associated optics. Potential defects associated with the fabrication process for thin film PV include shunts due to errors in the laser scribing step and increased susceptibility to corrosion. Further exploration of these technology-specific failure mechanisms is outside the scope of this article. The issue is nevertheless highlighted here to illustrate the complexity that results from the diversity of PV technologies.

Section 4: Common Failure Analysis Techniques

A variety of tools are available for the examination of failed PV system components, many of which have analogs or roots in microelectronics. Other microelectronics failure analysis techniques beyond those described in this section such as light beam induced current, lock-in thermography, electron beam induced current are also used in PV. Due to the nature of the most failure mechanisms highlighted in Table 1, however, a narrow subset of the techniques is used for most non-development situations. These methods are popular due to their effectiveness as well as their ability to be executed relatively economically and swiftly. This section describes the most common failure analysis techniques that were outlined in Table 1: IV measurements, electroluminescence, infrared imaging, and visual inspection.

Current-Voltage (IV) measurements provide baseline metrics on PV performance. The IV curve of a module or string of modules is similar to that of a group of diodes when in the dark. When exposed to light and generating power, the curve shifts negatively in voltage. This change signifies power generation since the curve no longer crosses the origin. Figure 1 shows an example of an IV measurement under illumination.

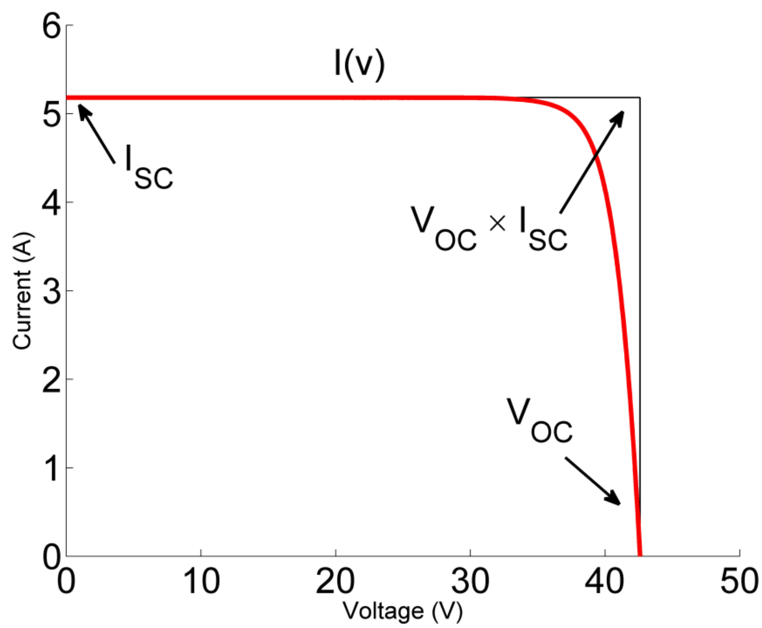

Figure 1: A typical IV curve (thick red line) under illumination that illustrates the definition of short circuit current and open circuit voltage. Note that positive current is defined here as the reverse bias direction to conform to popular convention in PV.

While an IV measurement by itself cannot pinpoint a particular failure mechanism, it can provide detailed performance information that can narrow the possible causes of diminished performance. Three important parameters are the short circuit current (Isc), the open circuit voltage (Voc), and the fill factor (FF). The short circuit current is the current generated at 0 volts or the intersection of the IV curve and the voltage axis. The open circuit voltage is the voltage observed at 0 amps or the intersection of the IV curve and the current axis. The fill factor quantifies the deviation of the IV curve, I(v), from an ideal rectangular shape that would generate a maximum power equal to Isc x Voc. The FF can be calculated by first integrating the IV curve from 0 V to Voc to find area under the curve (the thick red line in Figure 1). This quantity is then divided by Isc x Voc (the area under the thin black line in Figure 1):

$$FF = \frac{\int_0^{V_{oc}} I(v)dv}{I_{sc} \times V_{oc}}$$

An observed decrease in Isc, Voc, and FF can provide clues and guide subsequent failure analysis steps. Table 2 summarizes some failure mechanisms associated with changes in each of three parameters [9] [10].

Table 2: Possible causes behind changes in IV curve characteristics.

Parameter Change	Possible Causes
Isc	Encapsulant degradation, AR coating on glass or cell, loss of cell area due to cracking (in crystalline silicon) or corrosion (thin film).
Voc	Loss of cells, shorted bypass diode, shunted cell junctions, surface passivation loss.
FF	Corrosion of metallization, solder, interconnects, ribbons partially shunted cells.

The power of IV measurements is further enhanced if the data was acquired at various irradiance levels. For example, shunt resistance and diode issues have an outsized impact at lower irradiance levels. Interconnect issues have a greater impact at higher irradiance levels.

Electroluminescence is equivalent to light emission microscopy in microelectronics failure analysis and holds a similar role in photovoltaics. The device under test is placed under forward or reverse bias. The photons emitted by the device are the collected and imaged with a low-noise camera. The forward bias configuration measures cell performance while the reverse bias one locates leakage current paths that result from breakdown events. An example of an electroluminescence image is shown in Figure 2. As outlined in Table 1, electroluminescence can localize a large fraction of the failures described in this article. It can spatially pinpoint the failures that are suggested from IV measurements. While a high level of detail is possible, the technique generally requires removal of the module from the PV system and shipment to a laboratory for analysis. Therefore, electroluminescence is often used prior to system installation or after other in-situ techniques has been performed.

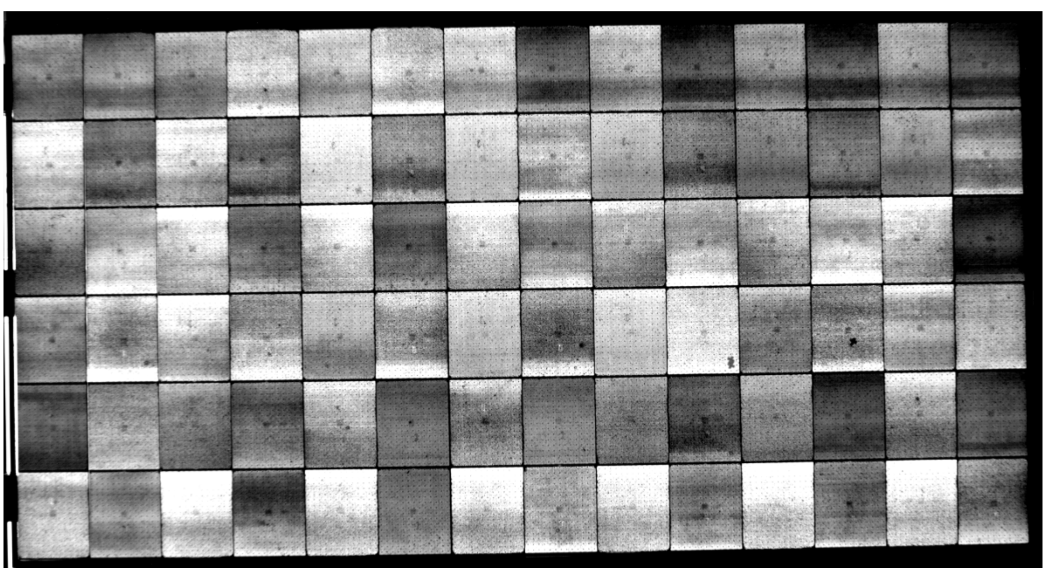

Figure 2: Electroluminescence image of a PV module, where regions with poor performance can be identified.

Infrared imaging captures the thermal signature of PV modules by a camera. The resulting image is similar to that shown in Figure 3. It is a useful tool for locating current flow paths. Infrared imaging is particularly valuable for health evaluation of installed PV installations because the measurement can be taken during system operation. Specifically, infrared imaging is a straightforward in-situ approach to detect hotspots.

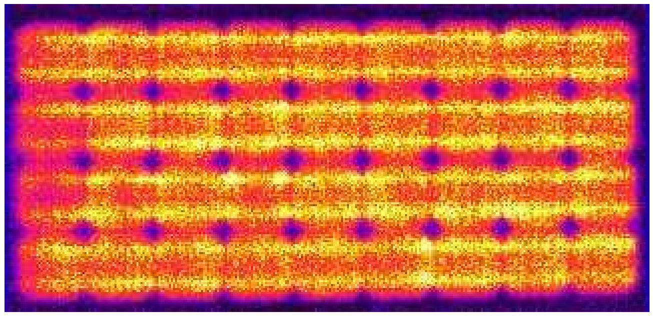

Figure 3: Infrared image of a PV module showing diminished current flow on the cells along the left edge.

Despite its simplicity visual inspection remains a critical technique for failure analysis in photovoltaics. Many failure mechanisms generate evidence that can be observed optically. Examples include delamination, hot spot damage, and encapsulate discoloration. While the evidence of the failure mechanisms are frequently visible without the aid of a scanning electron microscope, it remains relatively small compared to the area of the PV system. Therefore, as is the case with microelectronics, there remains the challenge and need for effective defect localization.

Section 5: Opportunities and Trends in PV Reliability

The techniques described in this article are analogous to well-established methods in the microelectronics failure analysis discipline. This section highlights future opportunities and trends in PV failure analysis and reliability that may be of interest to readers.

Development of tools and techniques for non-silicon PV will become increasingly important. PV cell technology is constantly evolving, resulting in exploration and development of a number of non-silicon materials systems. Sales growth for thin film photovoltaics, such as polycrystalline cadmium telluride (CdTe, with a band gap of 1.5 eV) and copper indium gallium selenide (CIGS, with a band gap of 1.0-1.6 eV) is greater than that of silicon PV [8]. Despite this growing market share, a majority of the tools for failure analysts in PV are designed for the silicon band gap of 1.1 eV. Development of alternative techniques centered on band gap values of future materials systems will become increasingly important.

Balance of systems (BOS) will gain importance in the push for lower levelized cost of energy. The reliability of the solar cells is becoming established and continues to improve as the industry matures. As a result of this improvement, BOS components are emerging as the new weak link in the PV system. BOS refers to all non-solar-cell components in the PV system. Examples of BOS components include inverters that perform the DC/AC power conversion, control software, connectors, combiner boxes, solar tracking, mounting racks, and junction boxes.

In particular, inverter failures are gaining increased attention for several reasons. As the pricing of PV modules continue to fall, the relative costs of inverter failures become significant. Failed inverters also have an outsized impact to the PV system, since a single inverter services multiple PV modules. Furthermore, financial constraints create pressure to utilize electronic components that are not suitable for harsh outdoor environments, such as electrolytic capacitors, leading to higher failure rates. The above reasons in conjunction with microelectronics expertise overlap make inverter failure analysis and reliability a potential opportunity for readers interested in the PV industry.

AC modules are a potential future solution to the reliability of power conversion system. AC modules refer to PV modules with built-in DC-AC power conversion circuits, also called “microinverters,” that output grid-compatible power. The lower output power of an individual module means that smaller circuit components can be used. This topology therefore distributes the risk, cost, and impact of individual power conversion component failures. It also, however, introduces new challenges that must be addressed prior to widespread adoption. The backside of the PV modules, where microinverters are housed, is a harsher environment due to the additional heat generated by the panel. Since the microinverter is tied to a module, it must match or exceed the 25-year lifetime expectation of solar cells — a difficult demand for power electronics. If AC modules overcome these challenges and attain widespread adoption, the microinverters will have similar components to that of microelectronic devices. This overlap represents another entry point for microelectronic failure analysts.

Section 6: Conclusion

PV failure analysis toolset has significant overlap with techniques and methods in microelectronics. This commonality provides opportunity for microelectronics failure analysts to contribute to the field of PV. Despite these similarities, PV faces unique challenges due to factors such as harsh operating environments and long target lifetimes. These issues are exacerbated by market characteristics such as cost pressures and industry fragmentation. These factors culminate in a rich field of research where experts from the comparatively-mature microelectronics industry may be able to provide unique perspective and contributions.

Section 7: Acknowledgements

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