Solar Cells, 27 (1989) 289 - 298

MEASUREMENT AND CHARACTERIZATION OF VOLTAGE- AND CURRENT-INDUCED DEGRADATION OF THIN-FILM PHOTOVOLTAIC MODULES

R. G. ROSS, Jr., G. R. MON, L. C. WEN and R. S. SUGIMURA

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109 (U.S.A.)

Summary

A number of important degradation mechanisms that determine the life of thin-film photovoltaic (PV) modules are driven by voltages and currents, either internal to the module, or between the module and its external mounting environment. Two important mechanisms are electromigration and electrochemical corrosion. Electromigration is current-induced diffusion of electrical conductors, such as the cell back metallization, at high current densities approaching 10^6 A cm^{-2} of conductor cross-section. Electrochemical corrosion is the transport of ionic elements in the presence of applied electric fields, and in the case of PV modules is generally associated with corrosion of internal cell materials as a result of leakage currents from the cell string to the module exterior. This paper reviews the status of JPL's research into these mechanisms as they affect thin-film modules of amorphous silicon (a-Si) and CdTe.

1. Introduction

An important element in achieving high-reliability thin-film modules is identification of the strengths and weaknesses of the available technologies. To this end, field aging studies, accelerated testing programs, and application experiments have been conducted, using a broad variety of both experimental and commercially available modules; the reliability attributes of these technologies have been examined at the level of cells and materials. In combination, these studies have led to a modestly complete definition of the design attributes required for long life, and have led to an ever-increasing number of commercially mature modules.

Recent JPL reliability studies have emphasized a variety of important degradation mechanisms caused by aberrant voltages and currents. These include electrochemical and galvanic corrosion [1 - 8], electromigration [9], and hot-spot heating [10]. Research results on two of these mechanisms — electromigration and electrochemical corrosion — are summarized here.

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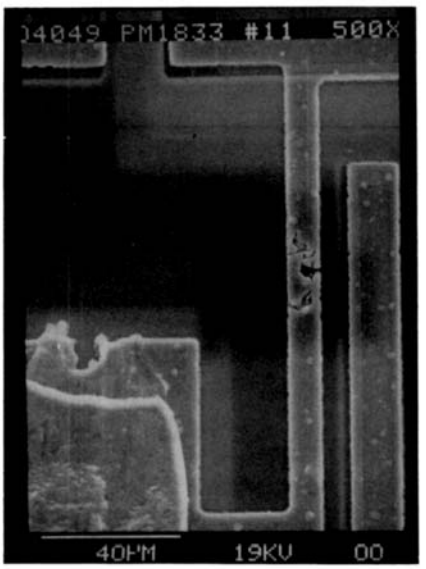
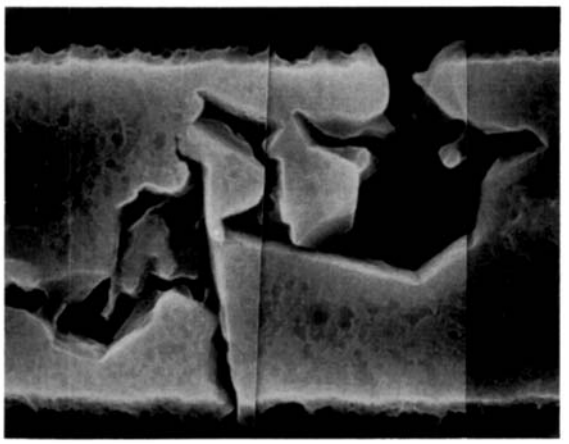
2. Electromigration research

Electromigration is a widely recognized reliability problem in thin-film aluminum microcircuits carrying high current densities [11 - 16]; the mechanism is an activated diffusion process wherein the applied electric field forces acting upon metallization atoms (activated ions) are overwhelmed by charge carrier (electron) momentum transfer forces. The result is current-induced transport of the metallization in the direction of the electron flow, which leads to the creation of metallization voids and possible open-circuiting, and/or to the creation of hillocks and whiskers. Figure 1 illustrates



(a)



(b)

Fig. 1. Scanning electron micrographs of electromigration damage in an integrated circuit.

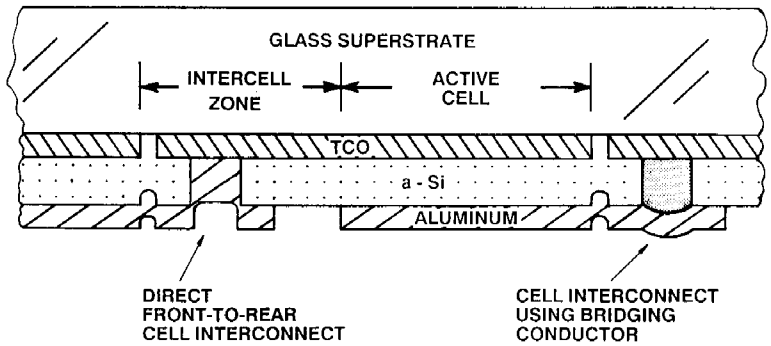


Fig. 2. Typical thin-film cell interconnection techniques.

typical electromigration damage in a modern integrated circuit conductor that carried a current density of 10^6 A cm^{-2} of conductor cross-sectional area. Generally, this electromigration mechanism becomes observable only at current densities above about 5×10^5 A cm^{-2}.

A common type of thin-film PV module features successive thin-film layers deposited on glass; these include transparent conductive oxide (TCO) directly on the glass, followed by the thin-film semiconductor layers and the aluminum metallization — the last applied by vapor deposition or sputtering to a nominal thickness of from 0.2 to 0.5 μm. Adjacent cells are electrically interconnected by selective overlapping of the thin-film layers such that the back metallization of one cell has a low-resistance path to the front surface TCO of an adjacent cell. As shown in Fig. 2, this conductive path can be implemented by scribing away the active semiconductor layer, thus allowing the deposited back metallization to contact directly the transparent front conductor, or by using a third metal — a bridging conductor — to bridge the gap between the back metallization and the front conductor.

In present state-of-the-art thin-film PV modules, metallization systems are generally called upon to carry currents of the order of 20 - 40 mA cm^{-1} width. The corresponding current density through a 0.4 μm metallization is about 8×10^2 A cm^{-2} — well below the 5×10^5 A cm^{-2} electromigration threshold. However, very high levels of local current density can exist in certain sensitive areas within the intercell zone, such as at the laser scribe lines. The critical question then is whether the electromigration degradation rate is sufficiently high in these regions to cause failure of the module within its intended life.

2.1. Test approach

To understand the possible role of electromigration in thin-film modules, JPL has conducted an extensive analytical and experimental investigation using a variety of specially made thin-film PV modules [9]. The approach involved developing a realistic criterion for determining test accelera-

tion factors, and then testing representative samples under accelerated conditions.

For the purpose of accelerated testing, special submodule test specimens were prepared for JPL by three leading manufacturers of amorphous silicon (a-Si) modules. These specimens were identical to commercial a-Si modules except that the back metallization was continuous from one cell to the next, not interrupted like the normal metallization configuration shown in Fig. 2. This continuous-metallization configuration contained all the laser-groove and bridging-conductor features of production modules, but allowed current to be passed from cell to cell without requiring conduction through the solar cell p–n junctions. Test specimens were fabricated by first cutting the fully metallized modules into strips of 2.5-cm width containing approximately 20 series-connected cells, and then attaching large copper conductors to each end. Accelerated testing was accomplished using d.c. currents in the range of 1 - 4 A for each specimen of 2.5-cm width.

2.2. Sample characterization

Because the sensitive laser-scribe areas are highly localized, direct observation and measurement of possible electromigration damage is extremely difficult; thus several experimental techniques were used to observe and assess the effects. Scanning electron micrographs and optical photographs were first made of pristine samples to identify regions susceptible to electromigration damage; the micrograph shown in Fig. 3 illustrates the discontinuity in the module back metallization where it traverses the laser-scribe interruption of the semiconductor layer, and suggests a probable thinning of the metallization as it attempts to cover this abrupt undercut step. Next, IR thermography was used to locate the scribe lines most likely to exhibit electromigration phenomena and to monitor temperature levels

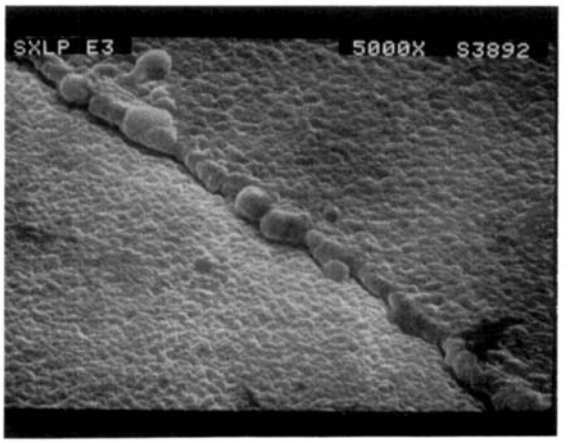


Fig. 3. Scanning electron micrograph of step in thin-film cell metallization as it traverses a laser scribe region.

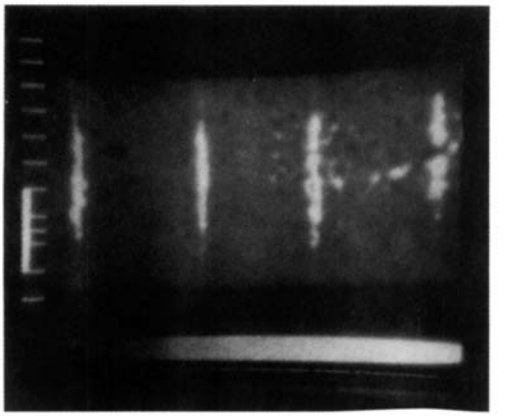


Fig. 4. Infrared thermograph of a module test sample, showing higher temperatures (lighter color) near laser scribes.

and gradients during applied-current accelerated testing. At a test current level below 40 mA cm^{-1} width, the samples were essentially isothermal. At a 1.2-A cm^{-1} current level, the IR thermography revealed that the sample scribe-line regions run 10 - 15 °C hotter than the baseline regions. The light regions in the IR thermograph shown in Fig. 4 represent the local thermal heating associated with the high resistance at the scribe-line edges. The wide variation in the observed temperature level also indicates that there are significant differences in the resistance along the various scribe-line edges.

To extract quantitative data from the IR images, a 40-node mathematical model was constructed and exercised to simulate the observed sample temperature levels and profiles. The current density concentration ratio along the scribe-line edges was assessed to be in the range 100 - 500 to produce the Joule heating required to match the observed temperatures. This level of current concentration is sufficient to exceed electromigration threshold levels.

Four-point microprobe resistance measurement techniques, performed under an optical microscope, were used to obtain quantitative resistance variations across the scribe lines, and within the baseline metallization. Although the vertical scribe line edges (about 0.2 - 0.4 μm) constitute no more than 4% of the total scribe-line width, the scribe-line edge resistance was found to be higher by a factor of 2 - 10 than that of the rest of the scribe line. This suggests that for pristine scribe lines, the local metallization thickness is not only significantly less than that of the baseline, but also varies widely among scribe lines. These measurements confirm the IR thermography observation, and verify the assessment of a 100 - 500 factor increase of scribe-line current density over baseline levels.

2.3. Electromigration life testing

To assess the susceptibility of the thin-film modules to long-term electromigration damage, representative module samples were also exposed

to prolonged exposure to accelerated current levels and high operating temperatures. During the exposure, periodic measurements were made of the scribe-line resistance using the precision four-point microprobes. In these tests all samples, except those metallized with high-purity aluminum, survived more than 2000 h of testing at a current density of 3×10^4 A cm^{-2} and a temperature of 82 °C. Detailed models relating the rate of degradation to applied current and operating temperatures were developed and used to assess the implications of the accelerated test program.

Is electromigration a reliability issue for thin-film modules? Based on the results of the present investigation, the answer appears to be no. Although module failures due to electromigration were observed in the laboratory, post-experiment analyses indicate that the acceleration factors associated with these experiments amount to lifetimes far in excess of 20 yr nominal operation.

3. Electrochemical corrosion research

Another current-induced degradation mechanism in thin-film PV modules is that of electrochemical corrosion. This mechanism is associated with the corrosion and transport of metal ions between the cell and the module frame under the influence of the large (100 - 500 V) cell-frame voltage potential present in applications with high system voltages above or below ground potential. The mechanism is found in modules of any design (crystalline and thin-film) where the module electrical insulation allows excessive leakage currents.

Previous JPL research over the last few years has extensively characterized the underlying physics of the mechanism, identified the controlling parameters, and recommended module design strategies to minimize its effects [1 - 8]. The solution to electrochemical corrosion lies in achieving low levels of leakage current through the use of encapsulants with low ionic conductivities, and through control of the ionic conductivity of encapsulant-free surfaces and interfaces. Thin-film modules using monolithically deposited cells on glass must additionally contend with the fact that the tin oxide transparent conductor often causes the front surface and edges of the glass to be electrically connected to the cell string.

Early field experience and testing of first-generation thin-film modules found many instances of unacceptably high module leakage currents, which resulted in excessive corrosion, and/or total breakdown and arcing through the module insulation system. As a final step in its corrosion research, JPL has focused, over the last year, on developing a simple, reliable qualification test to provide both a quantitative pass/fail verification of a module design, and diagnostic information on the location and nature of any excessive leakage currents.

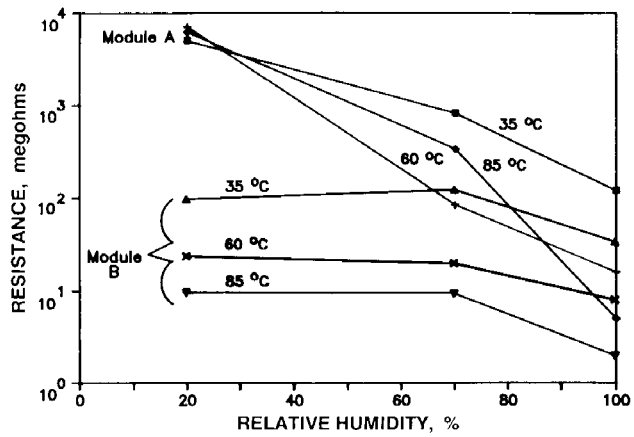


Fig. 5. Module leakage resistance on a function of environmental parameters (relative humidity and temperature).

3.1. Corrosion test development

The development of a corrosion qualification test was based heavily on the finding from the authors' previous research that module leakage currents are generally dominated by the strong dependency of ionic conductivity on moisture level [5, 7]. Field test results confirm that module leakage currents are generally orders of magnitude larger during periods of surface wetness such as dew, mist, and rain [5].

Drawing upon these findings, a range of test procedures of varying complexity were implemented at JPL on a trial basis. The most sophisticated attempted to simulate the actual distribution of module temperature–humidity conditions throughout the year [2], and the simplest concentrated on characterizing the module leakage resistance only under the conditions of complete surface wetness. Figure 5 illustrates module leakage resistance values for two representative module types under various temperature–humidity conditions recreated in an environmental test chamber.

3.2. Wet insulation resistance test

A much simpler apparatus, shown in Fig. 6, was used to conduct the tests with complete surface wetness. In this test, each edge of the module is dipped in sequence in a plastic trough containing a wetting solution, and a megohmmeter at 500 V d.c. is used to measure the resistance between the shorted cell string and the solution. The module is then stood on edge in the solution, and all surfaces including the junction box are sprayed with the same solution; megohmmeter readings are taken at time intervals of 0, 1, 2 and 5 min.

A particularly attractive feature of this test is the fact that any localized regions of low insulation resistance are accurately pinpointed during the spraying and dipping process.

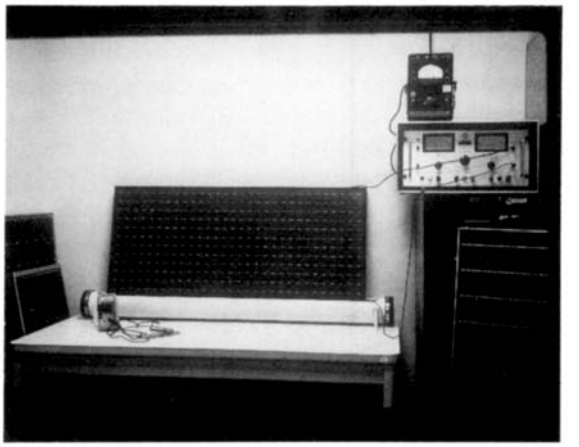


Fig. 6. Photograph of 'wet insulation resistance' test apparatus.

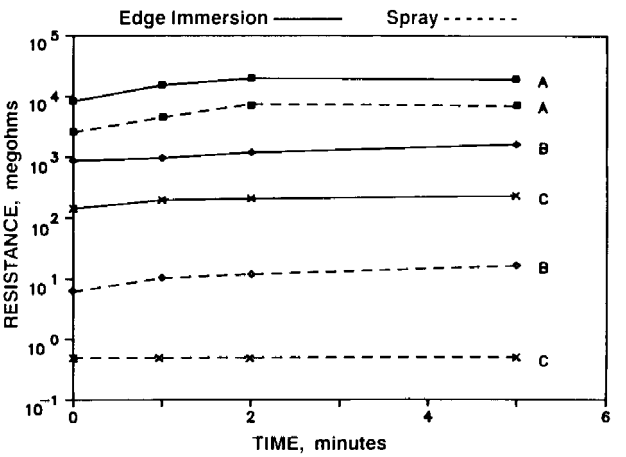


Fig. 7. Typical module leakage resistance response in wet insulation resistance test.

A plot of representative test module resistances using the above procedure (Fig. 7) indicates that the spray immediately lowers the resistance by more than two orders of magnitude (Modules B and C) for some modules, whereas for other modules the effect is either minimal or not immediate (Module A). Additionally, there is indication that 1 - 2 min is adequate for stabilization of current transients.

An important element of the test procedure is the inclusion of a high-quality wetting agent in the wetting solution to ensure complete surface wetting and elimination of water bead-up; water bead-up on the surface generally does not exist after a period of field aging and soiling, and therefore represents an unnatural high surface resistance condition. Several wetting agents capable of eliminating surface bead-up were tested; these

include Windex, Glass Plus, C. R. Laurence Glass Cleaner No. 695, Alconox and Triton X-100. Although all of the tested solutions performed quite similarly, the last is non-ionic and therefore potentially safer for application to production modules. The ionic content of the solution was found to have a negligible impact on the measured resistances.

Past JPL research on corrosion susceptibility of thin-film modules has provided quantitative data on the levels of integrated leakage currents that can be tolerated by typical thin-film cell constructions; this finding (0.1 C cm^{-1} of module periphery [8]), provides a rational foundation for establishing an initial pass/fail criterion for allowable leakage-current levels. Based on this value, the size of typical modules, and considerations of the likely number of hours of wetness, a pass/fail leakage current level in the range of 100 - 1000 MΩ seems appropriate.

3.3. Test verification

To test the validity of the above wet insulation resistance test, a number of representative thin-film modules are now being monitored in our JPL outdoor test site to provide *in situ* insulation resistance values for comparison with the values obtained on the same modules in the lab test. Results obtained to date suggest that the test is easy to implement and accurately reflects observed field performance.

Acknowledgments

This paper presents the results of one phase of research conducted at the Jet Propulsion Laboratory, California Institute of Technology, for the U.S. Department of Energy and the Solar Energy Research Institute, through an agreement with the National Aeronautics and Space Administration. The authors thank E. Jetter and S. Leland for their valuable assistance in performing the tests. Special thanks are extended to ARCO Solar, Inc. of Chatsworth, CA; Chronar Corporation of Princeton, NJ; Solarex Thin Film Division of Newtown, PA; and Sovonics Solar Systems of Troy, MI, who graciously provided thin-film modules and submodules used in this research.

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