

MEASUREMENT AND CHARACTERIZATION OF THIN-FILM MODULE RELIABILITY

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SUMMARY

As an indication of the evolving nature and continuing growth of photovoltaic technology, thin-film amorphous-silicon (a-Si) power modules have made their commercial debut during the past 2 years. Early experience with this technology has highlighted certain failure mechanisms as being the most important to long-term power generation. These include light-induced effects, corrosion of the cell monolithic interconnects, electrochemical corrosion between cells and module frame, hot-spot heating, and ultraviolet photodegradation of polymer encapsulants and frame members. Research at the Jet Propulsion Laboratory during 1987 has focused on measuring and characterizing many of these degradation mechanisms. Summary results are presented together with references to recent publications of detailed results in each area.

INTRODUCTION

A critical first step toward achieving high-reliability thin-film modules is identifying the strengths and weaknesses of the available technologies. To this end a variety of investigators have been conducting field aging studies, accelerated testing programs, and application experiments using a broad variety of first-generation a-Si modules [1]. Many additional investigators are examining the reliability attributes of this technology at the cell and materials level. In combination, these studies have led to a modestly complete definition of the research priorities for achieving reliable amorphous silicon modules and have led to a broad variety of ongoing solution-oriented research thrusts.

During 1987, the Jet Propulsion Laboratory, under the sponsorship of the U.S. Department of Energy and the Solar Energy Research Institute, has conducted a systematic study of the fundamentals underlying a variety of the important degradation mechanisms that involve materials and processes at the

module level. Key research thrusts have focused on measuring and characterizing four key mechanisms. These include:

- o Corrosion of cell interconnect regions
- o Electrochemical corrosion between cell string and module frame
- o Hot-spot cell heating
- o Ultraviolet photodegradation of module polymer encapsulants and frame materials

Findings are summarized in each of these areas.

CORROSION OF CELL INTERCONNECT REGIONS

Increased series resistance and module open-circuiting due to corrosion of the monolithic cell interconnect is perhaps second only to light-induced effects in its importance to a-Si module reliability. Because light-induced degradation reaches an acceptable equilibrium, corrosion may be more important in the long run.

The sensitive area of the module is the region shown in Fig. 1, where adjacent cells are electrically interconnected by selectively overlapping the thin-film layers such that the back metallization on one cell has a low-resistance ohmic conduction path to the front-surface transparent conductive oxide (TCO) of its neighboring cell. This conduction path can be implemented by scribing away the a-Si layer, thus allowing the deposited rear metallization to directly contact the transparent front conductor, or by using a third metal to bridge the gap between the rear metallization and the front conductor. Both techniques are used in commercial modules, and both have failure mechanisms associated with them. The key problems relate to sharp discontinuities and stresses in the rear metallization where it passes over the cliff-like edges of the laser scribe, and to galvanic couples between the dissimilar metals, when a bridging conductor is used. The back-lite photo shown in Fig. 2 displays two white lines along either edge of the front-contact scribe indicating open circuiting along each edge of the dissimilar metal used as the bridging conductor in this design. Similar open circuiting is found along the cliff-like edges of the scribe when the bridging conductor is not used.

Research is underway at JPL to fully understand the rate at which corrosion attacks these sensitive regions, and to develop means of minimizing the problem [2, 3]. Because an important element of the solution is controlling the ingress of moisture into the sensitive interconnect region, quantifying the rate of moisture ingress into various encapsulant systems is a key research focus. Particular emphasis is being placed on module designs where the cells reside between two layers of glass that are bonded together using a polymer adhesive such as Ethylene Vinyl Acetate (EVA). Fig. 3 displays special instrumentation used to measure the rate of moisture ingress by noting the moisture-dependent change in ionic conductivity between the inner

and outer electrode of each electrode pattern. By placing the patterns at various distances in from the module periphery, the time dependency of moisture diffusion has been determined. Other techniques that have been found useful include cobaltous chloride (color change) humidity sensors, and integrated circuit humidity sensors.

Although each method has its strengths and weaknesses, most are in agreement that the rate of moisture ingress into a glass-glass module is very slow. Time constants are on the order of thousands of hours to achieve significant moisture ingress.

Because these long time constants are in substantial disagreement with the 10 to 40 day time required to achieve significant series-resistance increase in 85°C 85%RH exposure tests [1], research has been recently expanded to examine the possible role of laser scribe lines and bridging conductors in providing preferential moisture diffusion paths. Fig. 4 is a recent photograph of the wicking action confirmed for one style of bridging conductor; the white bars represent the distance moisture wicked up from the lower edge of the module as measured using a special dye penetrant and photographed with ultraviolet light. These data suggest that it is important to ensure that preferential diffusion paths, such as a bridging conductor, not extend to the outer peripheries of the module, where they can make easy contact with external moisture sources.

ELECTROCHEMICAL CORROSION

Electrochemical corrosion between cell string and module frame has been the subject of extensive research at JPL over the past four years. This mechanism is associated with corrosion and transport of metal ions between cell and frame under the influence of the large 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.

A unique form of electrochemical corrosion, referred to as bar graph corrosion, has been recently observed with a-Si modules [1, 4]. In this mechanism, electrochemical corrosion attacks the tin oxide-glass interface causing delamination of the tin oxide from the glass. Ongoing experiments illustrated in Fig. 5 have confirmed that the corrosion is caused when the cells have a positive polarity relative to the frame, and excessive leakage currents exist:

The solution to electrochemical corrosion rests with achieving low leakage current levels through the use of encapsulants with low ionic conductivities, and through control of the ionic conductivity of encapsulant free surfaces and interfaces [5, 6, 7, 8]. Amorphous-Si 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.

Testing at JPL of modules with laser scribe interruption of the TCO conductor indicates that this technique is not sufficient as a high reliability insulation system. Numerous megohm-level resistance paths were commonly found between the cell string and module exterior edges of most commercially available a-Si power modules. This tin-oxide conductive path to the module exterior must be reliably interrupted and augmented with a high quality weather-resistant insulation system. Work on the development of such systems is actively underway.

HOT-SPOT CELL HEATING

Hot-spot heating occurs in a photovoltaic module when the short circuit current of a cell becomes lower than the string operating current, causing the affected cell to go into reverse bias and absorb power equal to the product of the cell reverse-bias voltage and the string current. The reduced short-circuit current can be caused by local partial shadowing or soiling, or by other degradation mechanisms such as glass cracking, or the "bar graph" corrosion noted earlier. Fig. 6 illustrates the cell erosion that occurs in a-Si cells under severe hot-spot heating conditions.

Significant research has been carried out at JPL over the past 3 years to understand the nature of hot-spot heating in a-Si modules, to devise test methods, and to develop recommendations to improve module endurance [9, 10]. The objective is to achieve modules that will safely endure commonly encountered levels of reverse biasing without suffering permanent hot-spot heating damage.

Since the degree of hot-spot heating is a function of the series-parallel configuration of the circuit in which the cell is located, there are circuit-design techniques that can be used, both in a module and in an array, to ameliorate the effects of the heating. For crystalline-silicon modules the primary technique is to limit the reverse bias voltage through the use of bypass diodes. A more important technique for a-Si modules is that of limiting current by scribing a module into two or more parallel strings of smaller cells [10]. Plots such as Fig. 7 are useful as guidelines for determining maximum cell size to limit hot-spot temperature to a given level [10].

ULTRAVIOLET PHOTODEGRADATION OF ENCAPSULANTS

A final element of the JPL research activity during 1987 has been focused on continued study of the effects of ultraviolet exposure on polymer encapsulants and frame materials. Previous study at JPL has extensively examined the photostability of encapsulant materials such as EVA as a function of both temperature and irradiance level [11, 12]. One limitation of the previous work was the inability to examine the effect of humidity level on the photodegradation process. This has been overcome through the development of a special aging chamber (Fig. 8) capable of accurately controlling sample temperature and humidity, while simultaneously providing a 1-sun ultraviolet irradiance level; the 1-sun UV level avoids the problems

of determining the non-linear acceleration factor associated with other UV flux levels. As a result, the chamber acceleration factor is dependent on the more easily established correlations associated with 24-hour-a-day exposure and increased temperature. In previous research at low humidity (1-sun UV, 85°C 5%RH), the acceleration factor of the chamber was determined to be from 7 to 70 depending on the normal operating temperature of the material in its intended application. This was done by comparing the known field performance of selected materials with the measured performance of the same materials in the chamber environment.

During 1987, research centered on evaluating the effects high humidity on the photostability of a wide variety of transparent Tedlar film materials, and on a limited number of plastic frame materials. Samples of these same materials were exposed previously to the 1-sun UV, 85°C test condition, with less than 5% humidity.

Results of the high humidity exposure indicated that humidity has only a small synergism with the photodegradation process of these materials. Times to failure, such as the cracking displayed in Fig. 9, were within 10 to 20 percent of the times determined with the absence of humidity. However, the level of degradation suggested that none of the tested materials is consistent with 30-year-life exposure as a front cover material.

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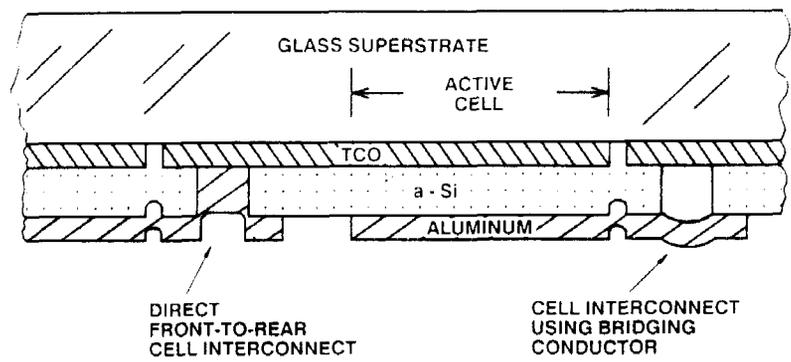


Fig. 1. Cross-section of typical monolithic interconnection of a-Si Cells on glass superstrate

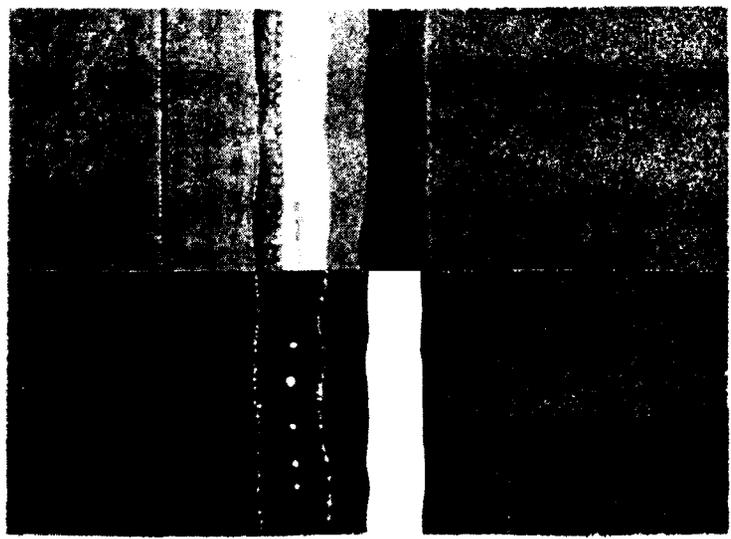


Fig. 2. Light dots in lower photo are metal voids (open circuiting) along bridging-conductor region of a-Si cell interconnect shown in upper photo

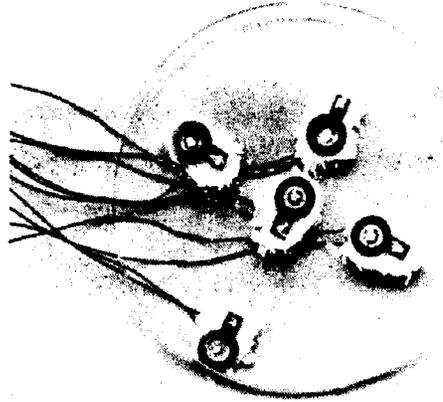


Fig. 3. Glass-glass sandwich (6-inch dia.) instrumented to measure moisture ingress

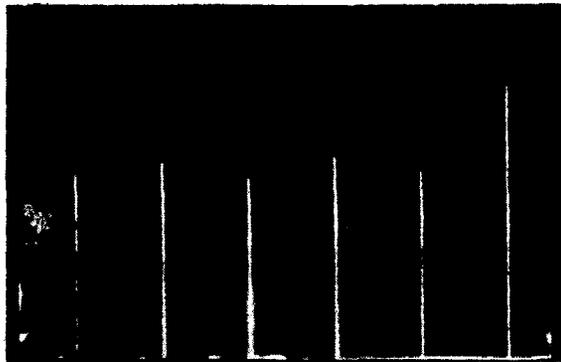


Fig. 4. Extent of moisture wicking up silver-frit bridging conductors made visible by dye penetrant

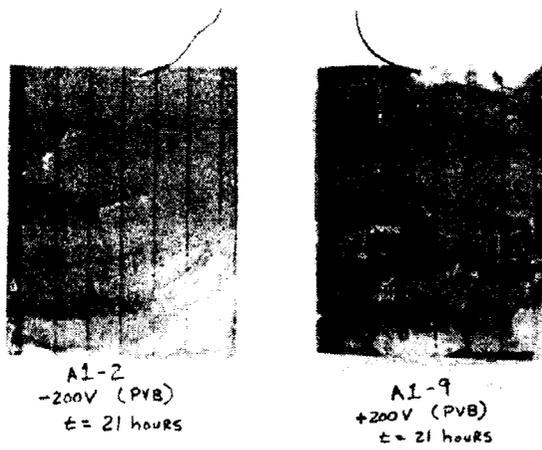


Fig. 5. Bar-graph corrosion visible in encapsulated a-Si test coupons stressed with applied potentials of ± 200 volts from cell string to external solution electrolyte.

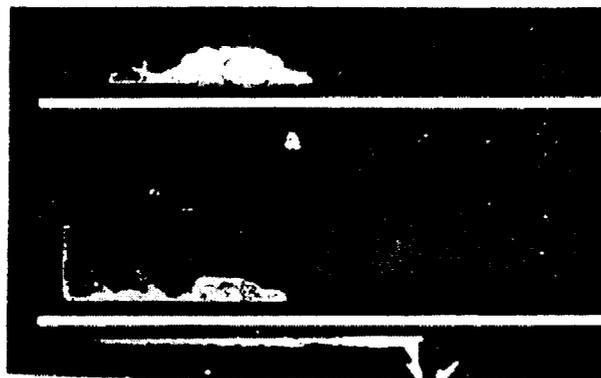


Fig. 6. Typical erosion of a-Si cells caused by severe hot-spot heating

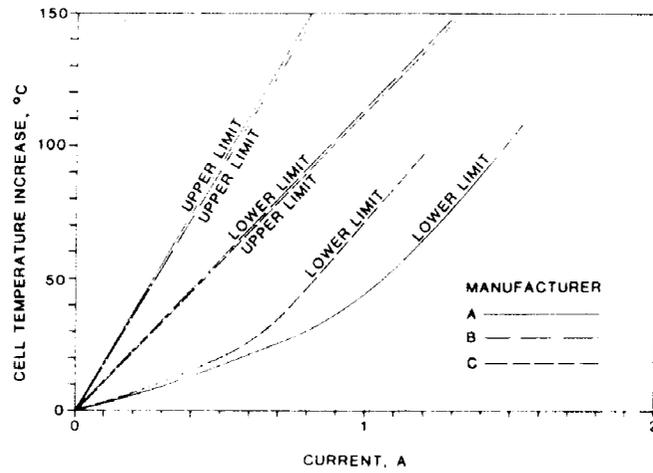


Fig. 7. Hot-spot temperature rise above operating temperature in large-area a-Si cells versus back-bias current

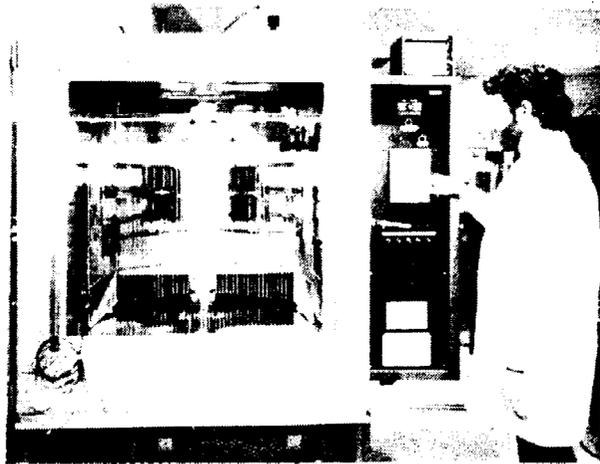


Fig. 8. Temperature-humidity-ultraviolet combined environment test chamber



Fig. 9. UV degradation of candidate vinyl backing films for thin-film modules