RECENT ACHIEVEMENTS IN MODULE RELIABILITY RESEARCH*

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ABSTRACT

After 10 years of extensive research on crystalline-silicon flat-plate photovoltaic modules, the emphasis of recent reliability research has shifted to the emerging first-generation thin-film amorphous-silicon modules. These new modules share much in common with their crystalline precursors, but also include many new materials and processes that demand the development of new reliability technologies. Key research thrusts include light-induced effects, cell corrosion, thermal diffusion, hot-spot heating, and electrical isolation of the cells from the module exterior. Research goals and recent achievements are described in each of these areas.

INTRODUCTION

Amorphous-silicon (a-Si) solar cells and modules are presently being used in a great diversity of applications ranging from small consumer products to prototype utility-scale electrical energy generation plants. Each of these applications has a unique requirement for performance stability and reliability that depends on the nature of the application.

Many consumer products, for example, are designed for full operation over a wide range of irradiances--from a dimly lit interior room to bright sunshine. Modest (e.g., 50%) degradation of the power performance of such an array only shows up at the lowest irradiance levels and is generally inconsequential to the application.

In contrast, energy-generation applications are sized for the highest prevailing irradiance levels and have little tolerance for array performance degradation. Based on this economic sensitivity to degradation, the national photovoltaics program of the U.S. Department of Energy has chosen a 30-year-life as a target goal for PV modules. It is this stringent 30-year-life goal that is the principal focus of the detailed reliability studies described here.

RELIABILITY TESTING OF a-SI MODULES

A critical first step toward achieving high-reliability modules is identifying the strengths and weaknesses of the available technologies. To this end a variety of investigators have and are conducting field aging studies, accelerated testing programs, and application experiments using a broad variety of first-generation a-Si modules. 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.

As a precursor to examining the mechanism-specific research activities, it is useful to review the general findings of the module-level tests. Although the majority of the results presented are drawn from our JPL test program, they are thought to be representative of the findings of the broader community; they also represent generic findings that are more or less applicable to most of the first generation and prototype a-Si power modules. The tested modules were all one square foot or larger in area and were from four manufacturers in the United States: ARCO Solar, Chronar, Solarex Thin-Film Division, and Sovonics.

Block V Qualification Testing Results

To assess the reliability attributes of the first-generation a-Si modules and to define priorities for required reliability research, a representative sample of a-Si modules was acquired from the four U.S. manufacturers and subjected to the standard

* 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.

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Proceedings of the 19th IEEE Photovoltaic Specialists Conference
New Orleans, Louisiana, May 4-8, 1987

Table 1. JPL Block V Module Qualification Tests

Test	Level and Duration
Temperature cycling	200 cycles; each cycle: 4 h, −40°C to +90°C
Humidity-freeze	10 cycles; each cycle: 20 h at 85°C, 85% RH followed by 4 h excursion to −40°C
Cyclic pressure loading	10000 cycles, ± 2400 Pa (± 50 lb/ft^2)
Wind resistance (shingles only)	Underwriters Lab Standard UL 997 1.7 k Pa (35 lb/ft^2)
Hail impact	10 impacts at most sensitive locations using 25.4 mm (1 in.) iceball at 23.2 m/sec (52 mph)
Electrical isolation	Leakage current ≤50 μA at twice worst-case system open circuit voltage plus 1000 V
Hot-spot endurance	3 cells back-biased to maximum bypass-diode voltage and cell-string current for 100 h of on-time

JPL Block V qualification test sequence outlined in Table I (1). This test sequence is in wide use for validating the suitability of crystalline-Si modules for field service and for identifying areas of design weakness.

A critical first step in the investigation was modifying JPL's Large Area Pulsed Solar Simulator (LAPSS) to ensure consistent, high-accuracy measurements of a-Si current-voltage performance under internationally recognized reference conditions. This was accomplished by filtering the LAPSS to provide a close-tolerance 100 mW/cm^2, Air Mass 1.5 Global spectrum, and by developing primary reference cells using high-efficiency crystalline-Si cells with their spectral response filtered to closely match that of typical a-Si cells. In combination, the LAPSS filtering and generic a-Si reference cells provide excellent 1% long-term-repeatability measurements of a-Si cells and modules without the need for detailed characterization of the spectral response of the cells and modules under test (2).

In general, the first-generation a-Si modules performed well in the Block V test sequence--comparable to the performance of first-generation crystalline-Si module designs. Such designs rarely pass the test completely, because of minor design deficiencies, but degradation levels are modest (on the order of 10%); a degradation of less than 5% is required to pass the Block V test.

It is useful to examine the detailed performance of the a-Si modules on a test-by-test basis to identify specific strengths and weaknesses.

Mechanical Loading Performance--Nearly all of the modules performed well in the mechanical loading tests, which include cyclic pressure loading, mechanical twist, and impact by 1 inch (2.5 cm) diameter hailstones. The one sensitive area was in the resistance to hail impact. Crystalline-Si modules have almost universally adopted 3 mm (0.125 inch) tempered glass superstrates to provide reliable protection against thermal stress and hail loads. When amorphous-Si cells are deposited on the rear of the module superstrate, the high-temperature tin-oxide coating process anneals the glass and generally requires that the glass be either structurally backed up or partially tempered. Large a-Si (30 cm x 30 cm) modules making use of 3 mm (0.125 inch) annealed glass were found to have difficulty passing the JPL Block V hail test; on the other hand, both structurally supported and partially-tempered a-Si glass modules met the requirement. The data indicate that glass strength is an important consideration with present-day modules, but is amenable to straightforward solutions.

Temperature-Humidity Endurance--This is the area where most of the modules exhibited minor problems involving softening and warping of plastic parts, some delamination of non-EVA systems, and power degradation due to increased series resistance. In one case, the series-resistance increase progressed all the way to module open circuiting. Because of the system sensitivity to power reduction and open-circuiting, the series-resistance increase was identified as a critical area requiring improvement.

Hot-Spot Endurance--During exploratory hot-spot testing, a-Si modules were found to have hot-spot heating characteristics quite similar to those of crystalline-Si modules, but were in some cases more tolerant than their crystalline counterparts (3). No problems were found with cells with maximum currents below about 400 ma; above this current high levels of hot-spot heating were encountered. Bypass diodes and other circuit changes provide readily available solutions for the sensitive high-current module designs.

Field Testing of Amorphous-Si Modules

Because the Block V test sequence was developed and refined specifically for crystalline-Si modules, another important first step was testing the applicability of the test procedure to amorphous-Si modules. This required careful comparison of real-time and accelerated field-aging results with those obtained in the Block V test sequence. Of specific concern was light-induced degradation, which is known to be important in a-Si modules, and which is not tested for in the Block V tests.

To obtain high quality field data, a representative sample of first-generation and prototype a-Si modules was placed in the field at JPL's main test site as shown in Fig. 1. Performance degradation was carefully monitored by periodically removing the modules and making precision I-V measurements using JPL's LAPSS measuring system. Control modules, stored in the dark at room ambient, validated the long-term 1% repeatability of the measuring system.

When mounted in the field, each module was electrically loaded to a specific electrical operating point on its I-V curve; some modules were loaded open circuit, some short circuit, and the majority were loaded at their maximum power point via a constant-voltage (zener diode) load.

Light induced effects were prominent in nearly all field-tested modules. As shown in Fig. 2, the degradation is typified by modest short-circuit

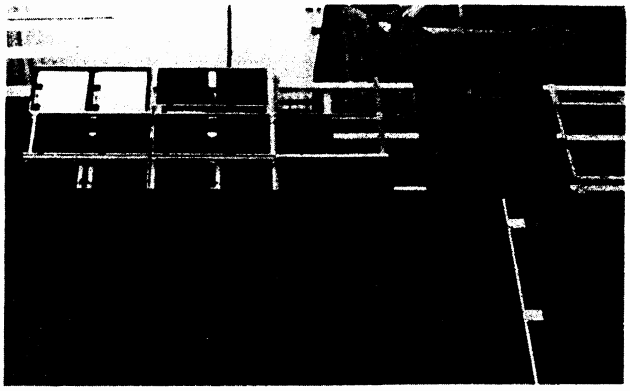

Fig. 1. Field Aging of First Generation a-Si Modules at JPL's Test Site

current loss accompanied with a shunt-like loss in fill factor. However, the initial rapid rate of degradation slows to a stable asymptotic level after a month or so of field exposure. Consistent with device testing experience, the electrical operating point of the module is also found to have a significant influence on the level and rate of degradation (Fig. 2). Although open-circuit modules generally degrade the most quickly, followed by those loaded at their peak-power point, some manufacturer's modules behave just the opposite. Because most power modules will be used with peak-power loading, this loading condition seems the most appropriate for field aging studies.

Theoretically, the rate of light-induced degradation should be minimal at elevated temperatures (above 90°C) due to increased thermal annealing of the degradation centers. This implies that aging studies conducted at elevated temperatures should be able to easily separate thermally activated degradation mechanisms, such as corrosion, from the thermally deactivated, light-induced degradation. To examine the usefulness of high-temperature aging, modules were also aged in the field at JPL, equipped with rear-side heaters to control the operating temperature. These modules were operated at peak-power loading at fixed elevated temperatures of 70°C, 85°C, and 100°C. For some of the modules the elevated temperature was imposed 24 hours each day; for the others the elevated temperature was only maintained during daylight hours. Unexpectedly, modules operated in the field at fixed elevated temperatures of 85°C and 100°C for daylight periods of 9 hours per day degraded very rapidly (Fig. 3), but stabilized at the same modest level of degradation as the unheated samples. However, at longer test durations corrosion mechanisms, suggested by the increased series resistance in Fig. 3, began to appear. After completing 160 days of testing, current-voltage (I-V) curve comparisons showed progressive series-resistance increases leading to total power losses as high as 62% for the 100°C samples.

For the 100°C samples that were heated continuously, the degradation was even further accelerated; degradation levels reached 93% after 40 days, and complete failure occurred after 80 days. Additional continuous-heating tests at 70°C revealed identical trends at the 80-day inspection period to those observed for the continuous 100°C heated modules. After that time, the degradation rate slowed (leveled off) compared to the rapid degradation observed from day 0 through day 40.

These elevated-temperature field-aging results do not agree with typical device-level laboratory

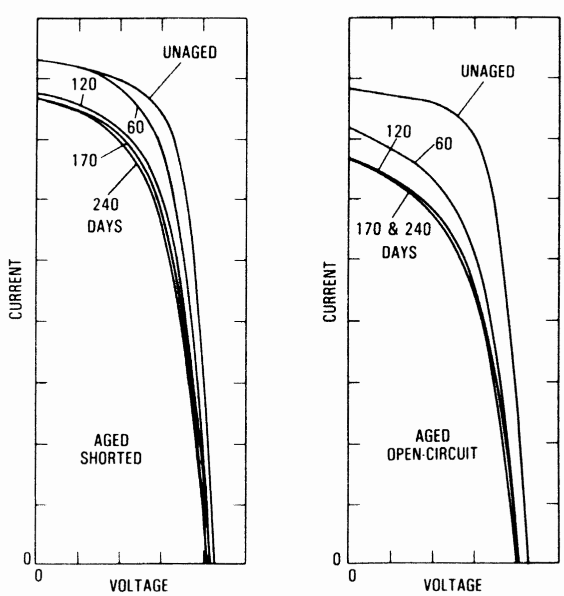

Fig. 2. I-V Performance Degradation due to Light Induced Effects Versus Outdoor Aging Period (Ambient Operating Temperature)

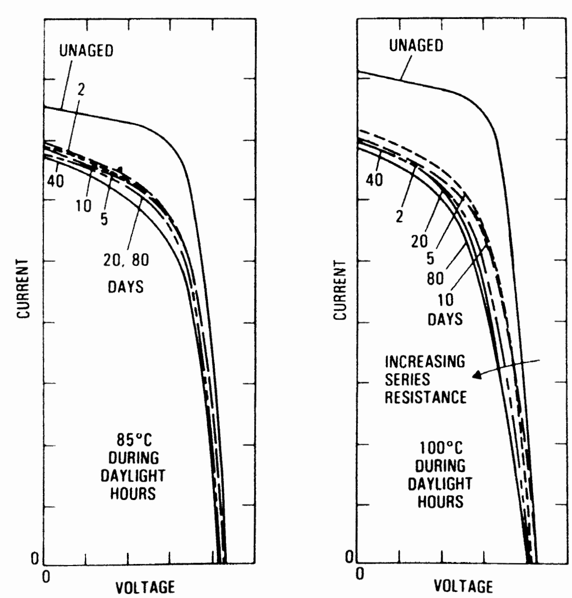

Fig. 3. Performance Degradation Due to Light Induced Effects fom a-Si Modules aged Outdoors at Elevated Temperatures.

testing and suggest that much is unknown relative to the parameters controlling light-induced degradation. As a check on the validity of the data the experiments were repeated elsewhere with similar results (4).

Accelerated Laboratory Aging Tests

In combination, the Block V qualification testing and the field aging reveal a number of degradation mechanisms important to a-Si modules and highlight the inadequacy of the Block V test procedure to predict the light-induced degradation observed in the field. To further understand the stress parameters influencing these mechanisms and to separate the interrelated effects of light-induced effects and cell corrosion, a number of a-Si modules were subjected to long-term testing in 85°C 5%RH and 85°C 85%RH dark-chamber environments. During the test a forward-voltage, reverse-current electrical bias was applied to 50% of the modules to stimulate the light-induced degradation mechanism. This current-induced degradation is considered to be indistinguishable from light-induced degradation, except that the rates of degradation are not easily comparable (5).

The following observations can be noted from the matrix of test results presented in Fig. 4.

1) No module degradation is noted under high-temperature low-humidity aging with no electrical bias.

2) The electrical bias causes a decrease in short-circuit current and fill factor similar to that associated with light-induced degradation in the field; however, the level of degradation is considerably less than that observed in field-aged modules.

3) High humidity causes rapid increases in module series resistance in a mechanism (corrosion of the cell interconnects) that is quite distinct from the light-induced degradation. This series-resistance increase is seen in the Block V humidity testing and is the same as that observed in the modules field-aged at elevated temperatures (without added humidity).

Application Experience with a-Si Modules

Although JPL has not been a direct participant in any field applications of a-Si modules, several large-scale test applications have been fielded by Chronar, Solarex Thin Film Division, and others, in collaboration with some of the electrical utilities in the U.S. These applications are an important complement to the laboratory and field-test aging experiments because they include additional user-interface stresses such as handling and installation loads, and additional system-interface stresses such as high cell-string-to-frame operating voltages; the large number of modules in these installations also greatly improves the statistical quantification of module reliability, and thus provides a better indication of the true importance of noted failures.

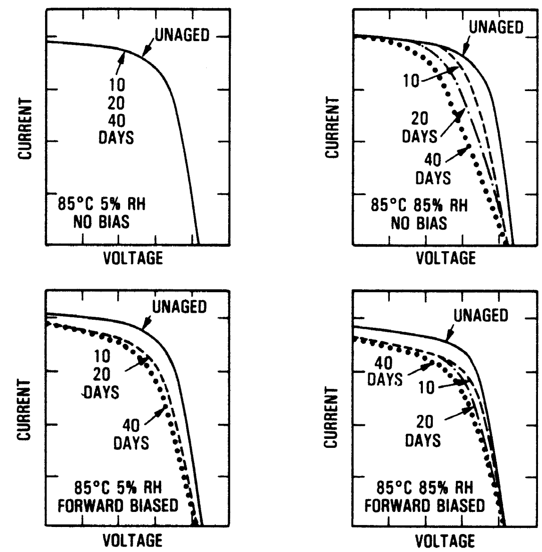

Fig. 4. I-V Performance of Representative Large-area a-Si Modules during Long-term Accelerated Aging

In discussions with these manufacturers it appears the application experiments are more or less collaborating the field-test results noted above, but are additionally emphasizing the importance and need for good electrical isolation between the monolithic cell string and the module/array frame.

Achieving good isolation between cell string and frame is particularly difficult with many amorphous-Si modules because of the presence of the conductive tin-oxide layer that effectively couples the cell string to the edges and exterior surfaces of the module glass superstrate. The environmental durability and long-term reliability of the often used laser-scribe interruption of the tin oxide film has been brought into serious question. Underwriters Laboratories describes detailed requirements in this area in their document Standard for Safety Flat-Plate Photovoltaic Modules and Panels (6).

In addition to the generic electrical isolation issue associated with ensuring electrical safety and preventing ground-fault arcing, achieving very low cell-frame leakage currents is also being found to be critically important to preventing electrochemical corrosion of the cells. Recently, Solarex has observed significant numbers of a-Si modules with "bar graph" delamination of the thin-film tin-oxide/cell stack from the glass superstrate (7). Pictured in Fig. 5, the delamination occurred in only the portion of their high-voltage array with a particular voltage relationship to ground. When another portion of the array was substituted for the degrading one, it soon began to develop the same "bar-graph" delamination. Because of the tie to the arrays voltage polarity, the mechanism is expected to be electrochemical in nature.

MECHANISM-SPECIFIC RESEARCH THRUSTS

The module-level testing and analysis described above has led to the identification of important degradation mechanisms in amorphous-Si modules that are actively being researched so that 30-year-life modules can become a reality. These include:

- o Light-induced degradation
- o Corrosion of the cell interconnection regions and back metal
- o Electrochemical corrosion between cell string and module frame including "bar graph" delamination of the tin oxide
- o Electrical breakdown and leakage currents between the cell string and module frame
- o Degradation of large-area a-Si cells due to hot-spot heating
- o Interdiffusion of dopants and chemical elements between the cell thin-film layers

Many of the recent achievements in enhanced module reliability are the result of numerous mechanism-specific research thrusts focused in these areas. Although it is beyond the scope of this paper to review all of these achievements in depth, it is useful to highlight some of the areas of research and progress.

Light-Induced Effects

Light induced effects are responsible for module degradation levels ranging from 15 to 50% during the first few months of field exposure. However, after this time the degradation slows significantly, appearing to stop at a stable equilibrium level (see Fig. 2). Many dozens of investigators are attempting to understand the fundamental physics of the mechanism, which has been found in all a-Si cells and modules, independent of important differences in cell manufacturing processes. The evidence to date suggests that the degradation mechanism is intrinsically coupled to the fundamental silicon-silicon atomic bonds associated with the a-Si material. Carriers (electrons and holes), either photogenerated or injected via an applied forward-voltage bias, are found to trigger the formation of metastable atomic defects when they recombine within the a-Si intrinsic layer; these defects then serve as recombination centers and carrier traps that reduce the output current from the cell. Open-circuit voltage is only minimally affected.

If the cell is heated to an elevated temperature (such as 160°C for 1/2 hour), the metastable defects anneal out and the cell is found to return to its original efficiency. The long-term stable equilibrium level of degradation at operating temperatures is thought to be an equilibrium between the rate of degradation and the lowered rate of annealing at this temperature. The presence of illumination and the concentration of

Fig. 5. Typical "Bar-Graph" Delamination of a-Si Cells from Glass Superstrate

hydrogen within the cell are additional factors that have been found to affect the rate of annealing.

Once the metastable defects are formed, the reduction in cell current output is dependent on the transit time required for a photo-generated carrier to pass from the intrinsic layer to the cell collectors; the current reduction is therefore dependent on the thickness of the i-layer and the level of the accelerating electric field internal to the cell. Because the internal electric field falls as the cell approaches open-circuit voltage, the current loss depends on the cell operating voltage and is manifested as the reduced fill factor noted in Fig. 2.

One means of reducing the light-induced current loss is to reduce the thickness of the cell i-layer (8). The inherently lower cell thickness associated with multiple-junction (tandem) cells has generally been responsible for lower levels of light-induced degradation in these devices.

Sabisky (9) presents an extensive summary of recent research on light-induced effects. Much of the latest research was reported on at the Conference on Stability of Amorphous Silicon Alloy Materials and Devices held in Palo Alto, California on January 28-30, 1987. The proceedings of the conference are due to be published by the American Institute of Physics.

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. Given that it does not reach an acceptable equilibrium, it may be more important in the long run.

The sensitive area of the module is the region shown in Fig. 6, 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

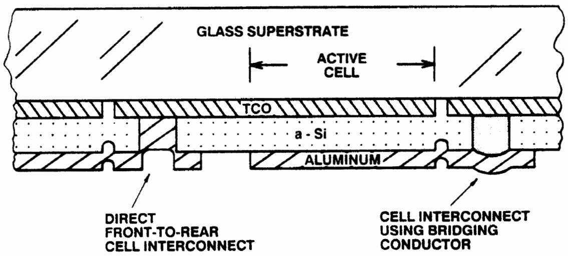

Fig. 6. Cross-section of Typical Monolithic Interconnection of a-Si Cells on Glass Superstrate

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, 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. 7 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 briding conductor in this design. Similar open circuiting is found along the cliff-like edges of the scribe when the briding conductor is not used.

Considerable research is underway to fully understand the rate at which corrosion attacks these sensitive regions and to develop means of minimizing the problem (10, 11). An important element of the solution is controlling the ingress of moisture into the sensitive interconnect region and using corrosion resistant metals and encapsulants.

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 a-Si) where the module electrical insulation allows excessive leakage currents. Fig. 8 shows an example of electrochemical corrosion found in a recent crystalline-Si system in an equatorial climate, whereas Fig. 5 shows a unique form of electrochemical corrosion observed with a-Si modules.

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

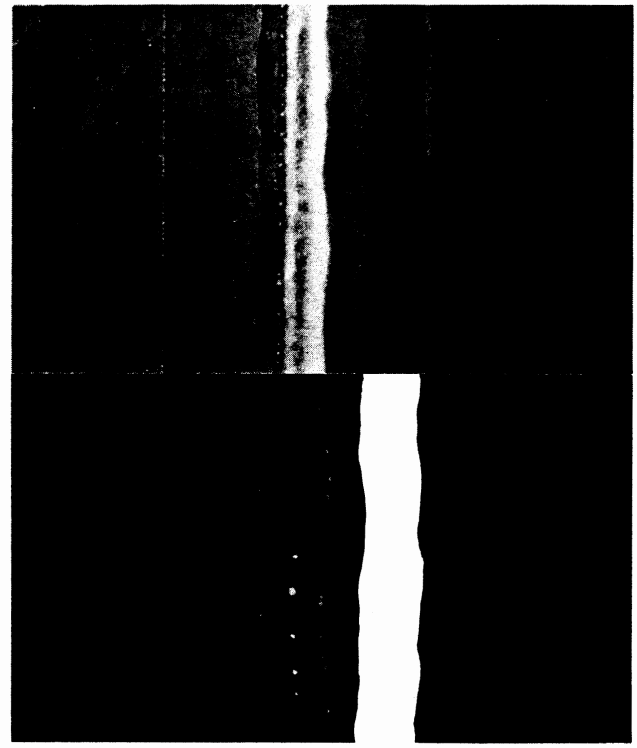

Fig. 7. Light Dots in Lower Photo are Metal Voids (open circuiting) along Bridging-Conductor Region of a-Si Cell Interconnect

conductivity of encapsulant free surfaces and interfaces (12, 13, 14, 15).

Module Shorts to Ground

When modules are intended for use in high-voltage (>50 volt) applications, the cell circuit must be reliably isolated from the module frame and external surfaces. The general requirement is that the module leakage current from cell string to external surfaces must be less than 50 μA when the applied voltage (cell to module exterior) is set to twice the worst-case system voltage plus 1000 volts. For most multi-kilowatt-size applications

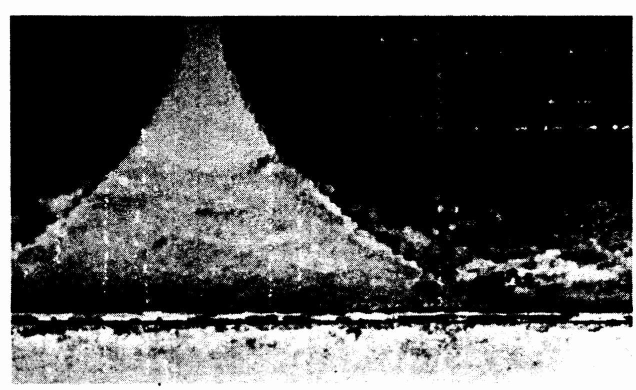

Fig. 8. Electrochemical Corrosion of Crystalline-Si Cells in High-voltage Equatorial Application

this (hi-pot) test voltage is in the range of 1500 to 3000 volts (6). Meeting this requirement demands great care in the design of the module electrical insulation system for any module, whether using crystalline-Si or a-Si cells. 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.

Initial 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, but this author is unaware of any published work to date.

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. 9 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 (3, 16). The objective is to achieve modules that will safely endure commonly encountered levels of reverse biasing without suffering permanent hot-spot heating damage.

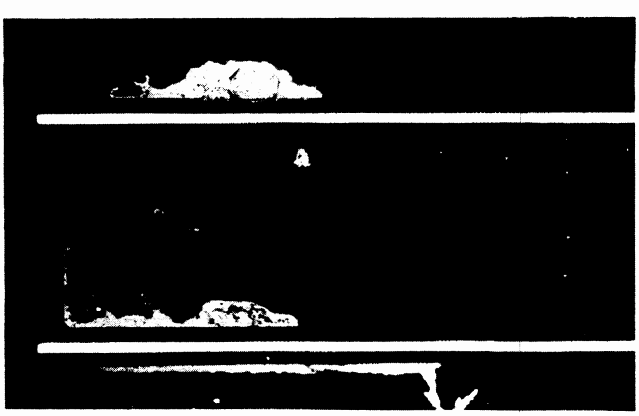

Fig. 9. Typical Erosion of a-Si Cells Caused by Severe Hot-Spot Heating

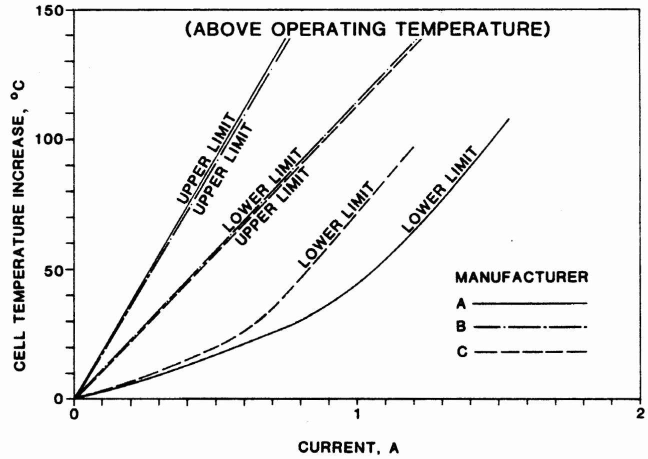

Fig. 10. Hot-Spot Temperature in Large-area a-Si Cells versus Back-bias Current

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-silicon modules is that of limiting current by scribing a module into two or more parallel strings of smaller cells (16). Plots such as Fig. 10 are useful as guidelines for determining maximum cell size to limit hot-spot temperature to a given level (16).

Thermal Diffusion Between Cell Layers

Another failure mechanism sometimes observed in a-Si cells is degradation of the cell I-V performance caused by thermal diffusion of elements into and among the cell's thin-film layers. Problems have occurred due to indium diffusion out of the indium-tin-oxide transparent conductor, boron diffusion out of the p-layer, and interdiffusion between the aluminum or silver back metal and the a-Si cell layers. High temperature (140°C) thermal aging tests have been found to be an effective means of accelerating this form of degradation (17). Most manufacturers have recently resolved the problem through the incorporation of various barrier layers such as tin oxide (without the indium) (18). Unfortunately most published data does not identify the actual barrier-layer materials used.

SUMMARY

As an indication of the evolving nature and continuing growth of photovoltaic technology, thin-film a-Si power modules have made their commercial debut during the past 2 years. Because of the extensive interest in this technology, the majority of recent reliability research has focused on characterizing the reliability of the first-generation a-Si power modules, and on initiating the development of reliability enhancements required to achieve 30-year life. Extensive field testing and early application experience have

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, electrical breakdown between cell string and frame, and diffusion of dopants and chemical elements between the thin-film cell layers. Research thrusts in each of these areas are actively underway and are making important contributions to the reliability of this promising technology.

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