HOT-SPOT DURABILITY TESTING OF AMORPHOUS CELLS AND MODULES*

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ABSTRACT

This paper discusses the results of a study to determine the hot-spot susceptibility of amorphous-silicon (α-Si) cells and modules, and to provide guidelines for reducing that susceptibility.

Amorphous-Si cells are shown to have hot-spot susceptibility levels similar to crystalline-silicon (C-Si) cells. This premise leads to the fact that the same general guidelines must apply to protecting α-Si cells from hot-spot stressing that apply to C-Si cells. Recommendations are made on ways of reducing α-Si module hot-spot susceptibility including the traditional method of using bypass diodes and a new method unique to thin-film cells, limiting the string current by limiting cell area.

INTRODUCTION

Hot-spot heating occurs in a photovoltaic module when the short-circuit current of a cell becomes lower than the string operating current, which causes 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. Field experience has demonstrated that hot-spot heating can lead to cell and module degradation.

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. The primary technique is the use of bypass diodes, which limit the reverse-bias voltage.

To determine the susceptibility of a module to hot-spot heating, which then defines the required frequency of bypass diodes, a laboratory test was developed at JPL (1, 2). Test conditions were created to simulate the thermal boundary conditions for 100 mW/cm^2, 40°C ambient environment. This test, which has been used extensively in the qualification testing of crystalline-silicon (C-Si) modules, formed the basis for the testing described in this paper.

OBJECTIVES

A key study objective was the quantification of the response of amorphous-silicon (α-Si) cells to reverse biasing. Lack of experience with cells composed of amorphous silicon led to the necessity of studying them in depth.

A second important objective was the development of guidelines which can be used by manufactures of α-Si modules and arrays to enable them to reduce hot-spot susceptibility. A third objective was to provide the photovoltaic community with a suitable hot-spot qualification test for α-Si modules.

APPROACH

Two types of cell configurations were tested—three- and four-inch-square submodules, and one-foot-square modules. One manufacturer's (Manufacturer A) submodules and modules differed in that the submodules utilized a 0.127 cm (0.05 in.) thick glass superstrate, whereas the modules had an added 0.32 cm (0.125 in.) thick glass substrate that allowed better heat dissipation under back-biasing. A second manufacturer's (Manufacturer B) modules and submodules were based on an 0.32 cm (0.125 in.) thick glass superstrate. A third manufacturer (Manufacturer C) provided a glass-superstrate test structure (0.182 cm [0.072 in.] thick), with small cells deposited on it.

Areas of cells in the various submodules ranged from 0.2 cm^2 (0.031 in.^{2}) to 7.1 cm^2 (1.1 in.^{2}), with most cells being larger than 4 cm^2 (0.62 in.^{2}). Areas of cells in two modules supplied by Manufacturers A and B ranged from 9.9 cm^2 (1.54 in.^{2}) to 33.4 cm^2 (5.18 in.^{2}), with the module with smaller cells having three in parallel.

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Selection of Test Parameters

There are two kinds of cell reverse-quadrant characteristics that must be considered when selecting hot-spot test parameters. One kind, which manifests high shunt resistance (type A), exists when the back-bias voltage V_L is established by the level of the applied voltage; the applied voltage is determined by the number of series cells per bypass diode, or the number of series cells in the array source circuit if no bypass diodes are used. In Figure 1, one can see that a partial shadow can bring a high-shunt-resistance cell to a point where it is reverse biased at a voltage V_L established by the voltage (curve -C) of the cells in series with it. However, the back-bias current, and the power dissipated, decrease to zero with decreasing illumination. As a result, high-shunt-resistance cells suffer the greatest amount of power dissipation under conditions of partial illumination.

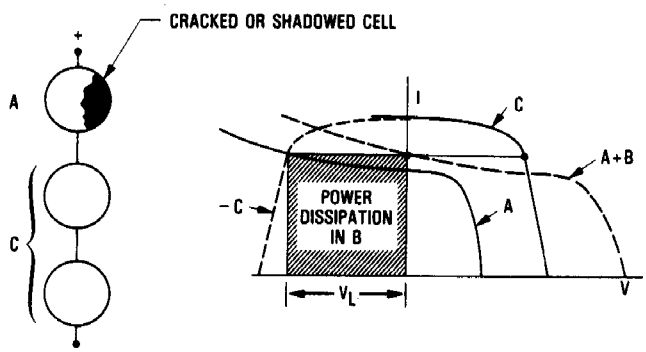

Figure 1. Visualization of hot-spot cell heating with a high-shunt-resistance cell.

The second kind of reverse-quadrant characteristic (type B) is associated with low-shunt-resistance cells, where the breakdown voltage V_B is less than V_L (see Figure 2). In this situation, the back-bias voltage is limited by the breakdown voltage V_B, not the number of series cells as defined in the above discussion of type A. V_B reaches its maximum value under conditions of no illumination; therefore, low-shunt-resistance cells suffer the greatest power dissipation when fully shadowed.

As the applied back-bias voltage increases without limit, all cells move into the low-shunt-resistance (type B) category because all cells have a finite breakdown voltage. Therefore, the test series described here began testing in the absence of added illumination to determine the region of voltage breakdown present in the α-Si cells.

Test Execution

The back-bias current and voltage were provided by a power supply, both by increasing the voltage gradually while the current was not limited, and increasing the current gradually while the voltage was not limited. In the voltage-control test, voltage breakdown occurred with a sharp increase in current. A chart recorder was used to record the reverse-quadrant

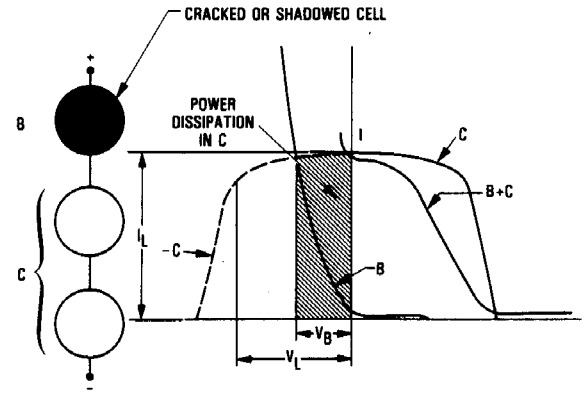

Figure 2. Visualization of hot-spot cell heating with a low-shunt-resistance cell.

response of the cell under test. In addition, the hot-spot temperature was measured with an infrared (IR) camera, using a black-body reference source. This method allowed accurate measurement of the breakdown voltage. The current control method is more effective for establishing the maximum current level that a cell can withstand (I_L, Figure 2). Both methods provided a parametric representation of power dissipation versus measured hot-spot temperature as the tests proceeded.

In addition to the exploratory testing described above, a standard 100-hour cyclic hot-spot susceptibility test was performed on cells in several 1 ft by 1 ft encapsulated modules containing about 20 series cells. These tests simulated operation at short circuit at a field operating temperature of 45-50 degrees C. The cells were treated as type B cells, and the tests were performed in the absence of added illumination.

Actual hot-spot-test acceptance criteria (2) require a visual inspection, a post-test electrical performance measurement, and a voltage isolation test, but the study discussed here did not involve the latter two tests.

Cell Contacting and Lead Attachment

Test procedures employed in the α-Si testing were essentially those used to test C-Si cells (1,2). The only major exceptions were the methods of accomplishing electrical contact to the cells. In the historical case of non-glass-backed C-Si modules, the backing is removed, and electrical leads are soldered to the metallization on the backs of the cells. The delicacy and non-solderable nature of thin-film cells necessitated development and application of new techniques for making electrical contact to the cells. A number of these techniques were employed.

One technique used a conductive elastomeric material clamped to the cell (Figure 3A). This technique had several advantages. First, the footprint of the contact on the cell metallization was large, lessening the risk of damage from highly localized currents. Second, a soft contact was provided, lessening the risk of cell damage due to abrasion. A disadvantage of this technique is that the currents required for back-biasing

cause the elastomeric material to deteriorate and lose conductivity, requiring constant changing of that substance.

A second technique involved the use of a spring-loaded probe contact (Figure 3B), where the contacts were pressed against the cell metallization by a soft spring. This method provides a positive contact that does not deteriorate, and which, if positioned with care, produces minimal damage to the cell backing. It is absolutely essential to use a contact large enough to carry the back-bias current, or the metallization will dissipate.

A third technique consisted of a ribbon lead, which was fastened to the metallization with conductive epoxy (Figure 3C). This technique requires a great deal of preparation for testing a large number of cells, but, once it is underway, the testing proceeds more rapidly with no risk of cell damage. Testing of modules with glass substrates requires that special test modules be prepared by the manufacturer. In this case, electrical contacts should be provided to each cell. Two of the modules tested were specially prepared glass-on-glass. Using conductive epoxy, a ribbon lead was attached to each cell at several points.

The three methods for providing contact to the cells all worked equally well as long as proper precautions were taken as noted.

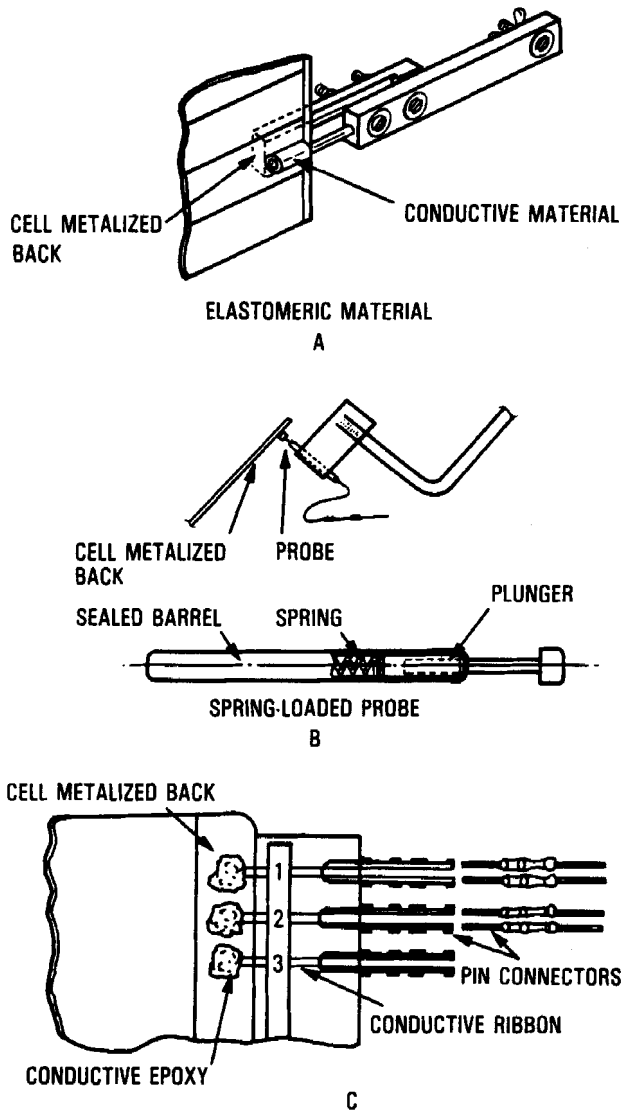

Figure 3. Methods of providing electrical connection to α-Si cells.

RESULTS AND CONCLUSIONS

Response of Amorphous-Si Cells to Reverse Biasing

The overall response of α-Si cells to back biasing is similar to that of C-Si cells, but with several notable exceptions. The most significant difference between the second-quadrant responses of α-Si and C-Si cells is the lower and more sharply defined breakdown voltage in the current-voltage curve of α-Si cells. The most important consequence is that a cell series with more than 10-15 cells will act as a type B cell, with the back-bias voltage being limited by the breakdown voltage. Therefore, hot-spot tests performed on modules with more than this number of cells should be performed in the absence of added illumination, as were the tests done in this study.

The only visual effects observed in these tests were cell erosion, glass cracking in thermal runaway situations with submodules, and a few instances of encapsulation discoloration. Cell erosion refers to the localized loss of cell material from the hot-spot area, and is shown in Figure 4, which is a photograph of one of the cells tested. Cell erosion can have two effects on cell performance. It can lead simply to the loss of power proportional to the loss of cell area, but it may lead to increased cell shunting as well.

Two of the three types of cells tested exhibited a dichotomous behaviour in their second-quadrant responses: (1) the response of a cell to initial back-biasing indicated a high shunt resistance, with a sharp voltage breakdown in the 8-to-12-volt range; the attendant hot-spot

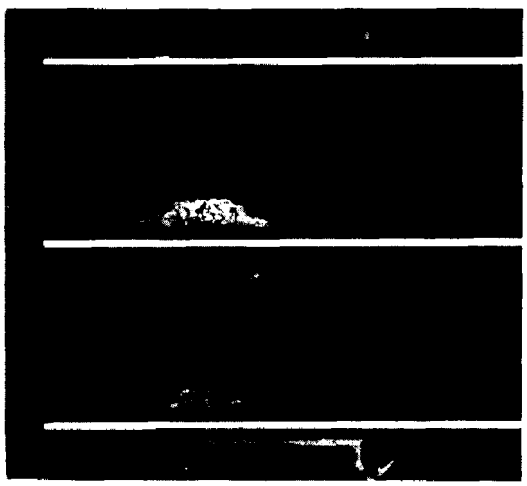

Figure 4. Example of cell erosion caused by back biasing.

resulted in a thermal runaway situation; and (2) after the cell was allowed to cool, its response to all subsequent back-biasing was characteristic of a cell with a lower shunt resistance; less power dissipation was required to achieve the same hot-spot temperature than in the initial case. Figure 5 compares some typical second-quadrant responses of the three types of cells tested.

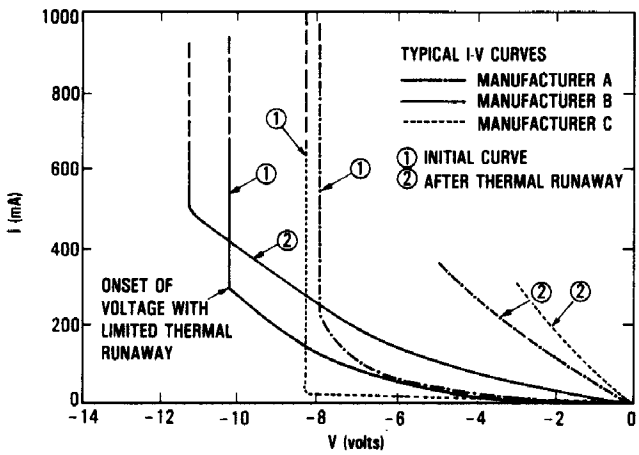

Figure 5. Typical α-Si cell second-quadrant I-V curves.

At the start of this study, one question asked was whether α-Si cells had different second-quadrant responses when tested under or without added illumination. Results of the tests performed in this study indicate that the second-quadrant responses of cells both with and without illumination are essentially the same, except for the translation of current with the irradiance level. Therefore, the only difference is the resultant increased power dissipation without added illumination, not the shape of the current-voltage response curve of the cell.

Hot-spot Temperature Versus Power Dissipated

The hot-spot temperature described here is the highest temperature resolvable with the IR camera used to monitor the tests. The power dissipated is the product of the applied current and the reverse-bias voltage across the cell at the point of current input. It is important to remember that the transparent conductor on the front of the cell is a poor one, making it difficult to correlate the measured voltage with the reverse voltage at the exact point of the hot-spot. Furthermore, the area of power dissipation varies from cell to cell, it being distributed over a number of highly localized hot-spots. Therefore, it is difficult to obtain an exact correlation between the highest temperature measured on the cell and the total power dissipated in the cell.

Despite these difficulties, it is useful to bound the range of expected temperatures for a given power dissipation because the temperature obtained can be related to the effects observed in cells and encapsulants. Experience with C-Si cells (1) indicates that the onset of degradation occurs in the 120-140°C range, with severe degradation occurring above this range.

Comparisons of several modules and submodules, illustrating temperature versus power dissipated, are shown in Figure 6, which shows the fraction of cells reaching a given temperature as a function of the power dissipated. Data are provided for both submodules and modules from the same manufacturer, where the modules had an added glass substrate and the submodules did not.

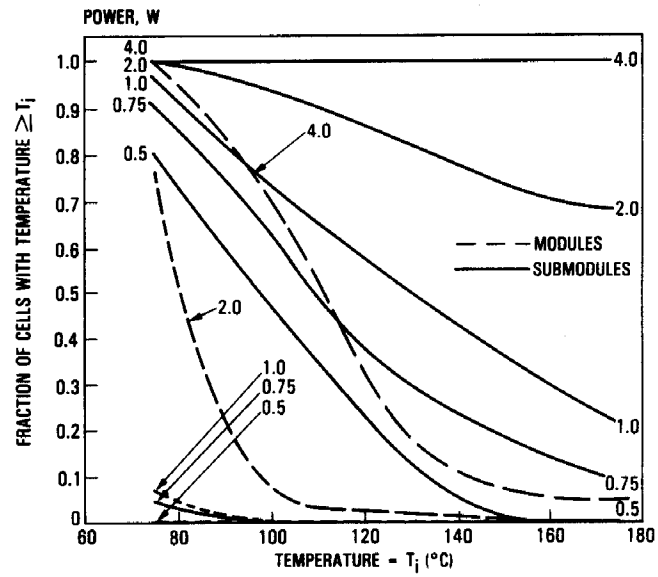

Figure 6. Fraction of cells reaching a given temperature as a function of power dissipated.

Figure 6 shows that the module glass substrate provides greater heat dissipation and, subsequently, lower temperatures. Figure 7 plots the dependency of temperature on power dissipated for a variety of modules and submodules, showing the amount of increase in temperature per unit of increase in power. The spread in data for the same manufacturer is a function of the nonlinearity of temperature as a function of power dissipation as discussed above. The variability between manufacturers is also a function of the differences in average reverse-quadrant cell characteristics and the heat-sinking capability of the modules.

The data used to plot the curves discussed in the last paragraph were obtained by gradually increasing the back-bias voltage with no current limit. Another set of back-bias tests were performed by limiting the current and rapidly increasing the voltage until the current limit was reached. The results of those tests, which simulated the actual occurrence of hot spots under field conditions, are shown in Figure 8 for the two different types of modules tested. Figure 8 shows the hot-spot temperature as a function of back-bias current. Tests were conducted using mainly integral values of 100 mA, with special emphasis given to values of 400 mA. Four hundred milliamps is the typical short-circuit current (measured at 100 mW/cm^2 and Nominal Operating Cell Temperature [NOCT]) of the 1 ft by 1 ft

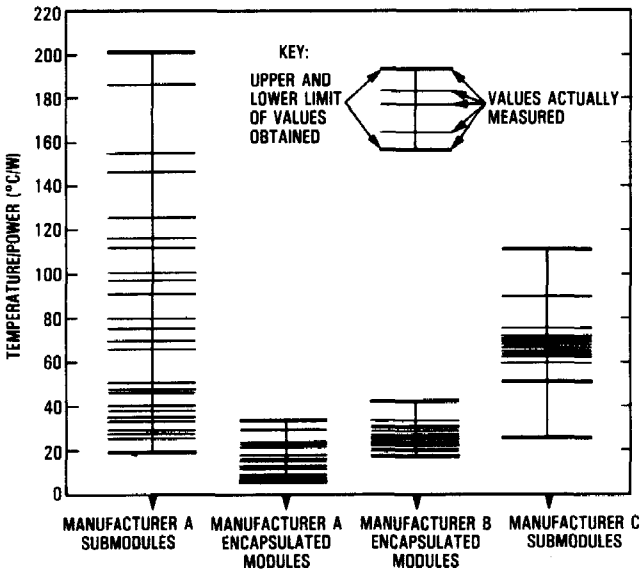

Figure 7. Rate of change of hot-spot temperature with power dissipated for submodules and encapsulated modules.

modules tested, and is also close to the upper bounds of the current range where hot-spot heating problems are not expected to occur. By observing plotted results in Figure 8, it is seen that, except in a few cases, temperatures did not increase beyond acceptable limits for currents less than 400 mA. The results obtained for currents of more than 400 mA indicate that hot-spot heating problems would occur unless bypass diodes were used. Therefore, if cells with short-circuit current greater than 400 mA (100 mW/cm^2, NOCT) are used, bypass diodes would be required about every ten cells.

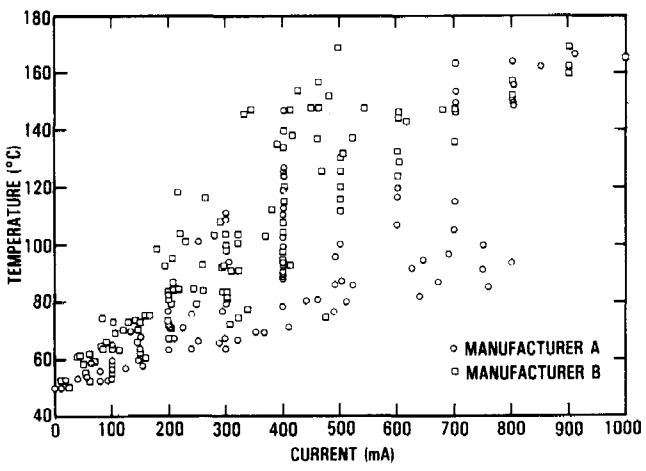

Figure 8. Hot-spot temperature versus back-bias current for encapsulated modules.

Guidelines for Reducing Hot-spot Susceptibility

The relatively low breakdown voltage of α-Si, cells makes current a key driver in controlling hot-spot heating. Since hot-spot heating is a focused phenomenon concentrated in a small region of the cell, the use of smaller cells with less current results in less heating. The long narrow shape of many α-Si cells makes them amenable to control of size by varying their length. If the module passes the hot-spot qualification test, the cell size is appropriate; if the module fails, the cell should be sectioned into smaller cells, if possible, and the test repeated.

The actual hot-spot temperature reached is also a strong function of the amount of heat sinking provided by the module. Thus, the thermal design of the module can be used to reduce susceptibility of the module to hot-spot heating. This fact is shown in Figure 6, where the hot-spot temperatures of submodules and modules are compared. On the average, the hot-spot temperature increase in the submodule was twice that in the module. The ratio between the total glass thickness (substrate, plus superstrate) contained by the module, and that contained by the submodule (superstrate only), is 3.5.

The use of bypass diodes to reduce back-bias voltage requires consideration of the low breakdown voltage of α-Si cells. If diodes are required, it means that the voltage must be reduced below 8-to-12-volts; therefore, the diode insertion frequency must be at least one diode every 10-15 cells. This conclusion implies that the diodes must be mounted internally in modules having more than 10-15 series cells. The use of diodes should be traded off against both reducing cell size to lower current, and improving heat sinking to reduce temperature.

Although there appears to be no reason for extensive cross-tying of parallel cells in an α-Si module, cross ties should be no more frequent than every six series cells to prevent current hogging by one of the parallel strings (3). Cross-tying of modules should not be a problem because of the large number of series cells in a module.

Hot-spot Qualification Test For α-Si Modules

The recommended hot-spot qualification test for α-Si modules (1,2) is basically the same as that for C-Si modules, with one notable exception. Crystalline-Si cells possess a diversity of second-quadrant characteristics, making it necessary to go through a cell selection process involving both high-shunt-resistance (type A) and low-shunt-resistance (type B) cells. Although a selection process is necessary when testing α-Si cells to obtain those cells which have the greatest hot-spot susceptibility, all cells in a module having a range of 10-15 series cells will be type B cells. Thus, hot-spot testing should be performed in the absence of added illumination.

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REFERENCES

1. Arnett, J.C., and Gonzalez, C.C., "Photovoltaic Module Hot-Spot Durability Design and Test Methods," Proceedings of the 15th Photovoltaic Specialists Conference, Orlando, Florida, May 12-15, 1981, pp. 1099-1105.

2. "Block V Solar Cell Module Design and Test Specifications for Intermediate-Load Applications, 1981," JPL Internal Document No. 5501-161, Jet Propulsion Laboratory, Pasadena, California, February 20, 1981.

3. Gonzalez, C.C., Weaver, R.W., Ross, R.G. Jr., Spencer, R., and Arnett, J.C., "Determination of Hot-Spot Susceptibility of Multistring Photovoltaic Modules in a Central-Station Application," Proceedings of the 17th IEEE Photovoltaic Specialists Conference, Orlando, Florida, May 1-4, 1984, pp. 668-675.