FIELD AND LABORATORY STUDIES OF THE STABILITY OF AMORPHOUS SILICON SOLAR CELLS AND MODULES

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ABSTRACT

If photovoltaic solar cells and modules are to be used as a major source of power generation it is important to have a good knowledge and understanding of their long-term performance under different climatic and operating conditions. A number of studies of the long-term performance of commercially available photovoltaic modules manufactured using different technologies have now been reported in the literature. These have shown clear differences in the seasonal and long term performance and stability. These studies are reviewed, with particular emphasis on performances in climates typical of the Asia-Pacific region.

In addition to general module engineering factors that result in a loss of performance in all modules some types of solar cells, such as those made from thin film amorphous silicon (a-Si:H), also suffer specific losses in performance due to fundamental material changes, such as photodegradation or the Staebler-Wronski effect (SWE). A field evaluation of the long term performance of state-of-the-art crystalline and amorphous silicon photovoltaic modules in Australian conditions is currently being undertaken at Murdoch University. The initial results from this monitoring program are reported. This paper also reports on laboratory and field studies being undertaken on the nature of the Staebler-Wronski effect in amorphous silicon solar cells and how the stability of these cells is affected by different operating conditions. Based on a mechanism for the SWE in a-Si:H solar cells developed as a result of our research we propose a number of possible ways to reduce the Staebler-Wronski effect in a-Si:H solar cells.

INTRODUCTION

The photovoltaic solar cell industry is currently enjoying strong growth, with 126 MW of PV cells shipped in 1997, which was a 42 percent increase from 1996 [Rannels, 1998]. With global PV installed capacity now exceeding 800 MW [Rannels, 1998] the indications are that the global PV industry is evolving beyond its former niche-market status into a fully grown, mature industry. There are four semiconductor materials at present in production or pre-production for solar cells, silicon wafers (c-Si), amorphous silicon (a-Si:H), cadmium telluride (CdTe) and copper indium diselenide (CuInSe$_2$ or CIS) [Hill, 1998], all of which are, or soon will be, commercially available as modules.

Commercial silicon wafer based cells have efficiencies around 14-17% for single crystal material and 12-14% for poly-crystalline (poly-Si) silicon wafers [Hill, 1998]. Amorphous silicon modules have been commercially available for many years. The output of a-Si:H modules made from single junction cells are seen to degrade in outdoor applications over a year or so by up to 30%, falling from an initial efficiency of 4-6% [Hill, 1998]. This degradation in a-Si:H modules, which is in addition to the general factors that result in loss of performance in all modules, is known as photodegradation, or the Staebler-Wronski effect (SWE). This effect was discovered over twenty years ago [Staebler and Wronski, 1977]. The SWE manifests itself as a decline in the photovoltaic conversion efficiency of a-Si:H solar cells with time under illumination [Wronski, 1984]. Typically the PV efficiency falls rapidly during the first few days of exposure to light, followed by a slower decay, which gradually approaches an asymptote over a period of several months. Until recently, a-Si:H modules made from multi-junction cells had an initial efficiency of 8-10%, and degraded less than single junction modules, between 10-20%. Guha [1997] has recently reported that United Solar Systems Corp (USSC) have developed, and are planning to commercialise, a triple junction a-Si:H solar cell with a stabilised efficiency of 13%. This gives the potential for commercial, stabilised a-Si:H modules above 10% efficiency. The long-term performance of these newer multi-junction a-Si:H modules has yet to be established as many of the new technology cells have not been in the field for very long.

CdTe/CdS modules are not yet commercially available but at present module efficiencies are around 8% and show no degradation either in the field or under accelerated testing [Hill, 1998]. CIS/CdS modules have
been in limited pre-commercial production for some years. Modules with an efficiency of 11% have been
demonstrated, but the average efficiency of the commercial modules is likely to be around 8% [Hill, 1998].

Single-crystal silicon continues to be the industry standard in PV markets, retaining a 49.6% market share
in 1997 with poly-Si having an increasing market share of 34.0% [Rannels, 1998]. Ribbon silicon
accounted for a further 3% of the 1997 market share [Hill, 1998], while a-Si:H had a market share of 11.8%
[Rannels, 1998]. The price for performance of PV cells has continued to improve, with the average price
being US$4.20/W in 1997 [Rannels, 1998]. Though PV continues to do well in remote markets and in
subsidiary building integrated PV applications, ultimately success in the broader market will depend on
getting the cost per watt low enough, and the value of the applications high enough to compete with
conventional energy alternatives without subsidy. One important factor in the success of PV as a power
generation source is the ability to guarantee long-term module performance and stability in a range of
different climatic conditions. It is therefore important to have knowledge and understanding of the long­
term performance of different types of photovoltaic solar cells and modules and to determine what
conditions affect module performance and reliability.

This paper will review a number of field and laboratory studies under different climatic conditions of
the long-term performance of photovoltaic modules manufactured using different technologies that have been
reported in the literature. It will also report on several different field and laboratory based research
programs being undertaken at Murdoch University to study the nature of the SWE in a-Si:H solar cells
and modules and how the stability of these cells and modules are affected by different operating conditions.
Based on a mechanism for the SWE in p-i-n a-Si:H solar cells developed as a result of our research over a
number of years some promising methods of reducing the SWE will be presented.

**REVIEW OF LONG TERM EVALUATIONS OF PHOTOVOLTAIC MODULE PERFORMANCE**

The PV industry now has a number of years of experience with the different types of modules under field
conditions and they have proven to be extremely reliable. This experience is also enabling an understanding
of the long-term outdoor module performance of different technologies to be obtained. As well as this, field
experience has allowed the development of procedures for accelerated testing which can mimic, over a few
weeks, the failures expected over a 30-year lifetime in the field [Hill, 1998]. There are a growing number of
reported studies of the long term performance of the different photovoltaic modules using both outdoor and
laboratory testing [Hawkins and Muirhead, 1996; Akhmad et al., 1997, Meike, 1998], and these will be
reviewed briefly.

Hawkins and Muirhead [1996] have reported a long-term evaluation of the performance and reliability of
photovoltaic modules manufactured using a number of different types of material. The various types of
modules they evaluated included c-Si, a-Si:H and CdS/CdTe modules. The modules were tested outdoors
under different climatic conditions expected for Australian operating conditions and included hot/dry,
hot/humid, marine, temperate and cold. The modules were also tested under modified laboratory conditions
to simulate exposure to in excess of 20 years in harsh Australian conditions. The results of the tests by
Muirhead and Hawkins [1996] showed that over eight years the greatest power loss observed for the c-Si
modules was of the order of 15%, but most modules exhibited power losses of around 5%. Over 7 years the
greatest power loss observed for a particular type of a-Si:H module was approximately 30%, but generally
the power losses were typically between 15 and 20%. For the CdS/CdTe modules power losses were less
than 10% over three years. Muirhead and Hawkins [1996] found there were a few problems common to both
the c-Si and a-Si:H modules, which affected some modules. The major ones were: EVA discolouration;
degradation of cell material; bubbling of rear Tedlar; and corrosion of tracks - yellowing of solder resin.

Akhmad et al., [1997] have reported results for the outdoor performance of a-Si:H and poly-Si PV modules.
They have used the daily integrated output power ($P_{int}$) and normalised daily watt-hour efficiency ($\eta_{wh}$)
of a-Si:H and poly-Si modules to examine the performance of both modules for a period of two years under
outdoor conditions in a hot, humid climate. For these experiments two modules, one single junction p-i-n a­
Si:H module and one poly-Si module, were installed adjacent to each other outdoors and their current­
voltage (I-V) characteristics measured in-situ. The results of Akmad et al., [1997] showed that during the
first year of exposure the $\eta_{wh}$ of the a-Si:H module degraded by a relative 18%. This degradation took place
predominantly in the first month of sunlight exposure, whereas it became negligible later on and the results
indicated that the efficiency of the a-Si:H module was almost stable during the second year. The $\eta_{wh}$ of the
poly-Si module remained almost unchanged even after 2 years of sunlight exposure, indicating no
noticeable degradation upon solar exposure for this period.
The results reported by Akhmad et al., [1997] also demonstrated the seasonal effects that are displayed by solar cell modules of different technologies. These results are reproduced in Figure 1. Their results have shown that the performances of both modules show significant differences, mainly in their daily watt-hour efficiency with respect to seasonal changes. As can be seen from Figure 1, the a-Si:H module profited from improved efficiency during the summer time, while it is the opposite for poly-Si, with a better performance being observed in winter. According to Akhmad et al., [1997] the rise in efficiency for a-Si:H samples in summer arises from two effects. A thermal-recovery effect (recovery of photodegradation) due to the increased temperature experienced during summertime is the dominant factor contributing to the improvement in efficiency. A second factor for the increase in the efficiency of the a-Si:H module is the more favorable spectral distribution of the solar irradiance during summer especially in the ultraviolet region. The poly-Si module does not profit in summer from the effects mentioned for the a-Si:H module. Variations in the output efficiency of the poly-Si samples is determined by the variation in band gap due to the cell temperature rather than by the solar spectral distribution, especially in the shorter wavelength region.

Meike [1998] has reported the results of an in-field study of Solarex poly-Si and Canon triple-junction a-Si:H solar cells in a fully operating power station located in a hot and humid zone. The results showed that the Solarex panels were twice as prone to ambient temperature induced output reductions than the Canon panels. Based on rated power, the overall power output of the a-Si:H panels in the test environment was between 20% and 30% higher than that of the poly-Si panels. Both Akmad [1997] and Meike [1998] recommend that for hot humid climates such as those in the Asia-Pacific region, a-Si:H solar cells should be used due to their enhanced performance in these climatic conditions compared to the rated power outputs.

Hof et al., [Private communication] have conducted a study of the long term behavior of passively heated or cooled Sanyo single junction a-Si:H modules. In their experiments they compared the outdoor performance of single junction a-Si:H PV modules which were mounted in three different ways. One was thermally well isolated against convection and radiation losses in a greenhouse box in order to reach maximum operating temperatures. A second one was fixed onto a radiator to keep its temperature as close as possible to that of the air. A third one served as a reference and was mounted with an open backside as a reference sample. By using different mountings they were able to strongly influence the operating temperature. All measurements done on the greenhouse module during the period of the study exceeded 80°C, even reaching temperatures up to 105°C. The temperature range of the reference sample was limited to 60°C, while that of the module fixed onto the radiator was restricted to 40°C or below.

Figure 2 shows the results of Hof et al [Private communication] for evolution of the average efficiency with time. These results show that although the higher temperature module started off at a lower efficiency, its efficiency stabilised much more quickly, and at a higher efficiency than the two lower temperature modules. The greenhouse sample’s efficiency stabilised after approximately 400 hours, whilst even after approximately 4000 hours the reference and radiator samples were still degrading. Hof et al., [Private communication] have conducted a study of the long term behavior of passively heated or cooled Sanyo single junction a-Si:H modules. In their experiments they compared the outdoor performance of single junction a-Si:H PV modules which were mounted in three different ways. One was thermally well isolated against convection and radiation losses in a greenhouse box in order to reach maximum operating temperatures. A second one was fixed onto a radiator to keep its temperature as close as possible to that of the air. A third one served as a reference and was mounted with an open backside as a reference sample. By using different mountings they were able to strongly influence the operating temperature. All measurements done on the greenhouse module during the period of the study exceeded 80°C, even reaching temperatures up to 105°C. The temperature range of the reference sample was limited to 60°C, while that of the module fixed onto the radiator was restricted to 40°C or below.

Figure 2: Evolution of average efficiency (normalised by the highest initial efficiency which was approximately 5%) for a-Si:H modules under different temperature conditions from the results of Hof et al. [Private communication]. The time scale refers to the beginning of the experiment.

Figure 1: Characteristics of the daily watt-hour efficiency (\(\eta_{wh}\)) of the a-Si:H and poly-Si modules normalised to their efficiency at standard testing conditions (STC). [Reproduced from Akxhmad et al., 1997]. \(T_{an}\) is daily average module temperature.
communication] conclude that in the long term a module mounting by which high operating temperatures are obtained has a beneficial effect on the conversion efficiency. A slightly lower initial efficiency due to the temperature is overcome by the reduction in photodegradation.

It is clear from these studies that the performance and stability of a-Si:H solar modules are dependent on the climatic conditions that they are operated under.

OUTDOOR MONITORING OF THE LONG TERM PERFORMANCE OF STATE-OF-THE-ART COMMERCIAL a-Si:H MODULES

Outdoor and laboratory studies of the long term stability of state-of-the-art commercial c-Si and a-Si:H solar cell modules are currently being undertaken at the Murdoch University Energy Research Institute (MUERI). The modules used in this study are commercially acquired BP165 c-Si modules procured from BP Solar and US-64 triple junction a-Si:H modules procured from Canon. Figure 3 shows the Pmax values (extrapolated to STC) for two of the a-Si:H samples over a 150 day period under open-circuit operations in normal field conditions.

From Figure 3 it can be seen that for both of the a-Si:H modules an initial sharp degradation in the output power is observed until a period of approximately 20 days has elapsed, after which the power output remains near the average degraded power indicated in Figure 3. Laboratory tests under a solar simulator corresponding to an outdoor exposure period of 45 days (1000 hrs) showed that these triple junction a-Si:H cells show a relative degradation of ~12.5%. Therefore it appears that the new triple junction technology modules are able to reduce the degradation due to the SWE to about 12.5% under normal operating conditions, with the modules stabilising after about 20 days in the field. The c-Si modules tested under the same conditions showed no noticeable degradation in output power over this 150 day period, either under field conditions or under the simulator.

OUTDOOR STUDIES OF COMMERCIAL a-Si:H SOLAR CELLS UNDER DIFFERENT OPERATING CONDITIONS

The results of Staebler et al., [1981] have suggested that the load conditions under which an a-Si:H solar cell operates can effect the rate and amount of degradation due to the SWE. In order to study the effect of different loads on the outdoor performance and long term stability of a-Si:H modules three commercially produced a-Si:H solar cell modules were operated under different load conditions in outdoor conditions for a period of 16 days. The NAPS A11P a-Si:H single junction solar cell modules were rated at 4 peak Watts under STC and all had similar efficiencies at the beginning of the study. One module was connected to a continuous resistive load of 11.5 ohms (equivalent to that needed for operation at the maximum power point at STC). One module was left at open circuit and one module was used to recharge a battery that was depleted at night to an 11.4 ohm resistive load. Figure 4 shows the efficiency with time for the modules operating under the three different external loads.

From Figure 4 it is clear that the load under which an a-Si:H solar cell module is operated can effect the degree of degradation of that module. Figure 4 shows that the module operated under open circuit conditions degraded the most (32%) after 13 days. The module operated under a load corresponding to that of normal operation near the maximum power point showed the least degradation (14%) after 13 days. The
module operating under battery charging conditions showed a degradation of 26% which was roughly the average of the other two. These results suggest that not only the climatic conditions, such as temperature, under which an a-Si:H module operates effect its degradation and long term performance, but so do the load conditions under which it is operated. Our results suggest that an a-Si:H module should always be kept operating under load conditions as close as possible to those of the maximum power point whilst under illumination. The module should never be exposed to illumination whilst under open circuit conditions, as this will lead to the largest degree of photodegradation in the module.

LABORATORY STUDIES OF THE NATURE OF PHOTODEGRADATION IN A-SI:H SOLAR CELLS AND MODULES

A series of a-Si:H samples and modules were exposed to simulated sunlight in the laboratory under open circuit conditions for periods of up to 500 hours in order to monitor their degradation due to the SWE in more detail, and to gain further insight into its mechanism. The single junction p-i-n a-Si:H devices used in this study were deposited by radio frequency glow discharge on textured indium tin oxide (ITO) glass substrates. The light soaking experiments were carried out using a solar simulator, which produced light intensity close to AM1.5 sunlight at temperatures that did not exceed 40° C in any of the experiments. The samples were tested before and after each exposure to illumination by measuring the light and dark current voltage (I-V) characteristics at AM1.5 for a number of spots on each sample. The efficiency values were calculated from these I-V characteristics. Figure 5 shows the typical decline in the photovoltaic conversion efficiency with time under illumination for a typical laboratory p-i-n a-Si:H solar cell.

The degradation profile in Figure 5 shows three regions. The photovoltaic efficiency of the sample falls very rapidly during the first 10 or so hours, losing about 10 to 11% of its efficiency during this period. This is the first region. After this the efficiency falls less rapidly during the next 100 or so hours of exposure to light, losing a further 13 to 14% of its original efficiency during this period. This is the second region. The two regions of rapid decay are then followed by a slower exponential decay approaching an asymptote at the stabilised efficiency over a period of about a month, this is the third region. The sample in Figure 5 showed a final decay of about 27% of its original efficiency after it had stabilised. This is similar to that observed in earlier, single junction a-Si:H solar cells, where samples showed a relative decay in efficiency of up to 30%. Some modern designs have reduced the degradation in a-Si:H solar cells to around 10% [Zemen and Schropp, 1994; Guha et al., 1996]. Figure 6 shows the efficiency values for an NAPS single junction a-Si:H module exposed to simulated AM1.5 sunlight in the laboratory for a period of 115 hours whilst connected to an external load of 70.2 ohms. This degradation profile is similar to that of the commercial a-Si:H solar cell module in Figure 5, showing three similar regions. The module in Figure 6 showed a final decay of about 22% of its original efficiency after it had stabilised. The results of Figure 6 confirm that the a-Si:H cells produced in our laboratory are similar to those produced in commercial single junction modules and show the same degradation profile.
Over a number of years our group has carried out a careful study of photodegradation in a-Si:H in order to understand the mechanism of the SWE. Infrared absorption spectroscopy, combined with light soaking and theoretical modeling, has provided insight into the mechanism of photodegradation enabling us to explain some aspects of the SWE [Clare et al., 1996]. Our proposed mechanism, which has been described in detail elsewhere [Clare et al., 1996], appears to explain all of the known characteristics of the SWE and has enabled us to propose [Lund et al., 1997] a number of materials engineering methods for limiting the photodegradation in a-Si:H solar cells. These methods include:

- the use of light trapping to promote the uniform illumination of the material
- hydrogen enrichment of the p-layer to provide a larger pool of hydrogen atoms to promote healing of the lattice, thus reducing the demand for hydrogen from the bulk; and
- the use of a micro-crystalline p-layer, which is less susceptible to degradation in the first place.

Some of these methods suggested by our model for reducing the SWE are now being used in new device structures [Lund et al., 1997; Okamoto, 1994; Schropp 1996] and their effectiveness in reducing the SWE is being tested. Guha [1997] has recently reported that United Solar Systems Corp (USSC) have developed and are planning to commercialise a triple junction a-Si:H solar cell with a stabilised efficiency of 13%. These new triple junction cells will need to be tested for long-term stability and performance.

CONCLUSIONS
A number of studies of the long-term performance of photovoltaic (PV) modules using different techniques under different climatic conditions have now been reported and these modules have proven extremely reliable. In addition to the general engineering factors that result in a loss in performance in all modules, solar cells made from amorphous silicon (a-Si:H) have been shown to also suffer losses in performance due to photodegradation or the Staebler-Wronski effect (SWE). These losses range from up to 30% for single junction devices to 10-20% for triple junction devices.

Our field and laboratory studies of state-of-the-art triple junction a-Si:H solar cell modules have shown that these modules undergo an initial sharp relative degradation of ~12.5% over a period of 20 days in the field, then remain stable. Field studies of single junction solar cell modules under different loads have shown that not only do climatic conditions, such as temperature, effect the degradation of a-Si:H modules, but so do the load conditions under which they are operated. From our studies we recommend that a-Si:H modules should always be connected to load conditions as close to their maximum power point as possible whilst under illumination and they should never be exposed to illumination whilst under open circuit conditions.

More detailed studies of the SWE in single junction a-Si:H cells and modules have shown that they appear to have a degradation profile with three distinct regions. The photovoltaic efficiency appears to fall very rapidly during the first 10 to 20 hours, losing from 10 to 13% of the relative efficiency. This is followed by a period where the efficiency falls less rapidly for the next 60 to 100 hours of exposure to light, losing a further 10 to 13% of the efficiency. These two regions are followed by a third region of slower decay, which approaches an asymptote at the stabilised efficiency over the period of a month or so. These and other studies have enabled us to propose a mechanism for the SWE and to propose a number of materials engineering methods for limiting the photodegradation in a-Si:H solar cells.

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REFERENCES


