DEGRADATION STUDIES OF A-SI:H SOLAR CELL MODULES UNDER DIFFERENT LOADS IN THE FIELD

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ABSTRACT

A number of field and laboratory studies of the performance of commercially available amorphous silicon (a-Si:H) photovoltaic modules have been reported in the literature. These have shown clear differences in the performance and stability of these modules under different seasonal and temperature conditions. This paper reports on laboratory and field studies being undertaken on the nature of the Staebler-Wronski effect in commercial single and triple junction a-Si:H solar cells and how the stability of these cells is affected by different operating conditions. Degradation profiles of a-Si:H modules operated under different loads are reported and the implications for the operation and handling of such modules in the field are discussed.

INTRODUCTION

Single-crystal silicon continued to be the industry standard in PV markets in 1997, retaining a 49.6% market share, with poly-Si having an increasing market share of 34.0%, and a-Si:H having a market share of 11.8% [Rannels, 1998]. The price of power from 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 subsidised 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 climatic and operational conditions affect module performance and reliability.

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, which was discovered over twenty years ago [Staebler and Wronski, 1977] 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.

This paper will present the results of a study of the nature of the SWE in commercial single and triple junction a-Si:H solar cell modules and how the stability of these modules is affected by operation under different load conditions. Based on these results some suggestions for the operation of a-Si:H modules in the field will be presented.

PREVIOUS STUDIES OF PERFORMANCE AND STABILITY IN A-SI:H MODULES

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 now a growing number of reported studies of the performance and stability of different commercial a-Si:H modules under different conditions using both outdoor and laboratory testing [Akhmad *et al.*, 1997, Meike, 1998, Rüther and Livingstone, 1994].

Meike [1998] has reported the results of a field study of Solarex poly-Si and Canon triple-junction a-Si:H solar cells in an operating power station located in a hot and humid zone of Australia. The results showed that the Solarex panels were effected more by 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.

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_{wh}) and normalised daily watt-hour efficiency ($\_{wh}$) 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 $\_{wh}$ of the a-Si:H modules degraded by 18% relative to their initial efficiency. 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 $\_{wh}$ 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. Their results have shown that the performances of both the a-Si:H and poly-Si modules show significant differences, mainly in their daily watt-hour efficiency, with respect to seasonal changes. 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 summer time 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.

Rüther and Livingstone [1994] have studied the seasonal variations in amorphous silicon solar module outputs in order to explain the reasons for the improved efficiency of a-Si:H solar cells in summer. They have been able to gain further understanding of the role played in the seasonal variation by the two mechanisms attributed by Akhmad et al [1997]. By exposing commercial a-Si:H solar modules to the same AM 1.0 spectrum under open circuit conditions while keeping them at temperatures corresponding to extreme summer and winter operating cell temperatures they have concluded that the second effect, seasonal spectral variations in the radiation reaching the earth's surface might be the major factor in the overall seasonal efficiency changes. They believe that recovery due to thermal annealing only accounts for between 2 and 4% of the 10% recovery, at normal summer operating temperatures.

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 these 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.

The results of Hof *et al* [Private communication] for evolution of the average efficiency with time showed 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] 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 soon 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 under which they are operated. There appear to be less results published showing the performance and stability of commercial a-Si:H modules under different operating conditions, such as load. Most performance and stability studies have also focussed on the long-term performance and stability of the modules, with measurements typically being taken on a daily basis, Therefore more detailed information about the degradation pattern of these modules in the early stages of the degradation is not known.

RESULTS

Outdoor studies of commercial single junction a-Si:H solar cells under different loads

In order to gain more detailed information about the degradation profile of commercial a-Si:H solar cell modules during the first hours and days of operation the efficiency values were measured on a regular basis for a 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, shown in Figure 1, shows three distinct regions. The module in figure 1 showed a final decay of about 22% of its original efficiency after it had stabilised.

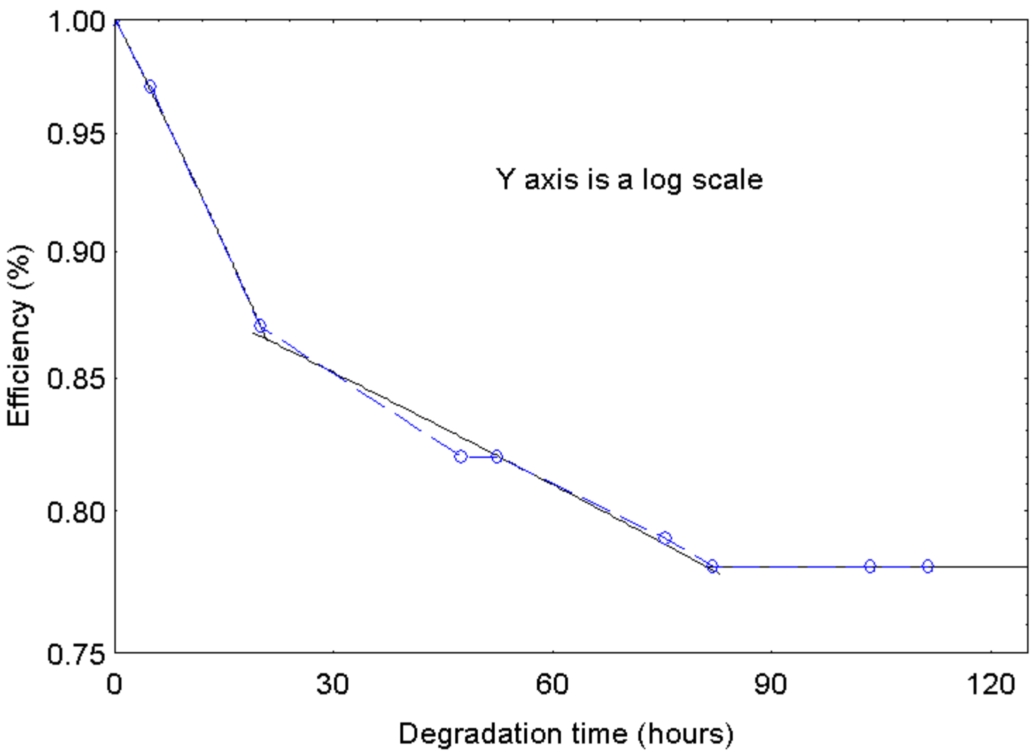

Figure 1: Typical degradation profile for a single junction commercial *p-i-n* a-Si:H solar cell module exposed to AM1.5 illumination in a solar simulator. Vertical axis is a log scale. A linear fit to the data is shown as a solid line. The efficiency is given as a percentage of the original module efficiency before exposure.

This three stage degradation profile in Figure 1 is similar to that reported before [Lund *et al.*, 1999] for a series of laboratory produced a-Si:H samples exposed to simulated sunlight of AM1 intensity in the laboratory under open circuit conditions for periods of up to 500 hours. These single junction *p-i-n* a-Si:H devices were deposited by radio frequency glow discharge on textured indium tin oxide (ITO) glass substrates. The degradation profile from these samples also showed three regions. The photovoltaic efficiency of the sample fell very rapidly during the first 10 or so hours, losing about 10 to 11% of its efficiency during this first period. 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 second period. The two regions of rapid decay were 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 laboratory samples showed a final decay of about 27% of their original efficiency after they had stabilised, which 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%. It appears therefore that the commercial single junction modules behave similarly to the single junction laboratory samples, with a similar degradation profile.

In order to study the effect of different loads on the outdoor performance and long term stability of single junction a-Si:H modules three commercially produced single junction a-Si:H solar cell modules were operated under different load conditions in outdoor conditions for a period of 13 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 2 shows the efficiency with time for the modules operating under the three different external loads. The measured outputs from the three test modules have been scaled using the output from an unexposed reference cell in order to account for any differences due to the measurement system.

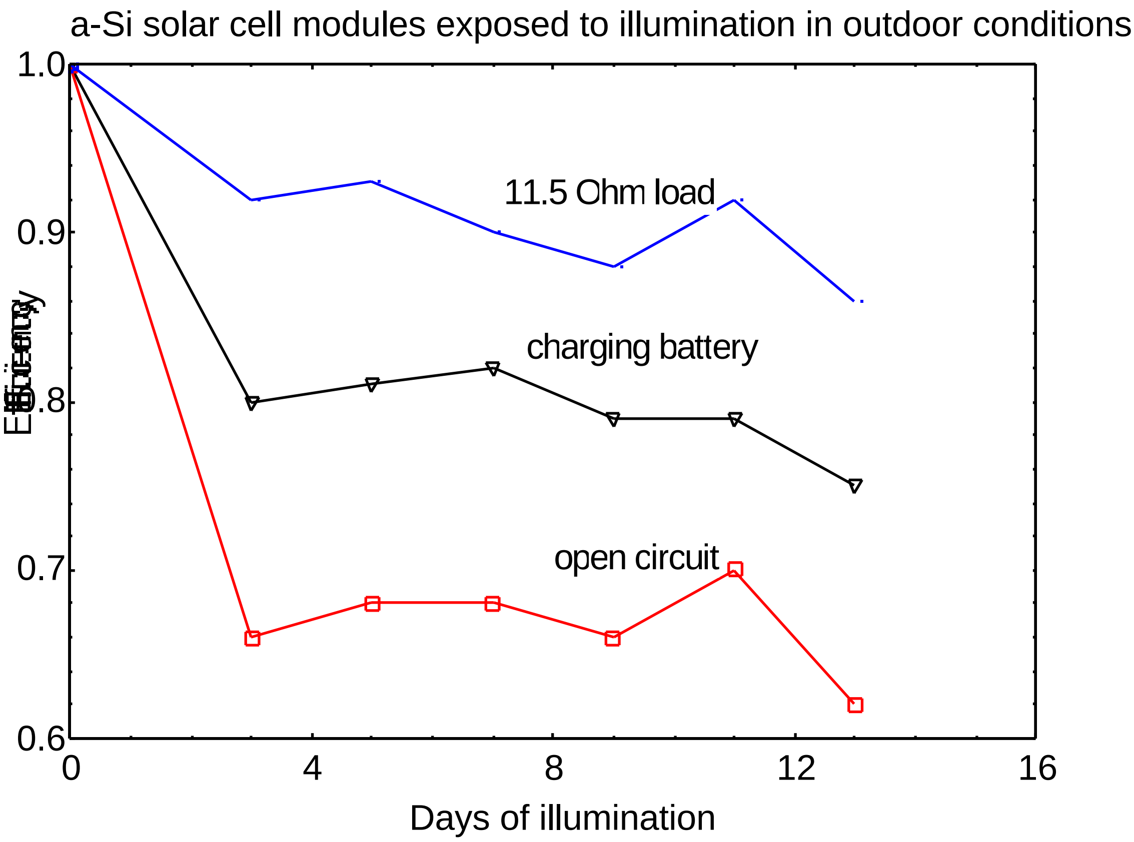

Figure 2: Measured efficiency versus time profiles for single junction a-Si:H solar cell modules exposed to illumination in the field whilst connected to different loads. The efficiency is given as a fraction of the original module efficiency before exposure.

From Figure 2 it is clear that the load under which an a-Si:H solar cell module is operated can also affect the rate and degree of degradation of that module. Figure 2 shows that the module operated under open circuit conditions (largest resistance) 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%. . These results clearly 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.

Outdoor studies of commercial triple junction a-Si:H solar cells operated under different loads

Outdoor studies of the long term stability of state-of-the-art commercial triple junction a-Si:H solar cell modules have been reported previously [Lund *et al.*, 1999]. The modules used in these studies were commercially produced USSC US-64 triple junction modules. The modules were operated over a 150 day period under open-circuit operations in normal field conditions. Both of the a-Si:H modules showed an initial sharp degradation in the output power until a period of approximately 20 days had elapsed, after which for the remainder of the 500 hours of measurement the power output remained near the average degraded power. Laboratory tests under a solar simulator corresponding to an outdoor exposure period of 45 days (1000 hrs) at open circuit 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.

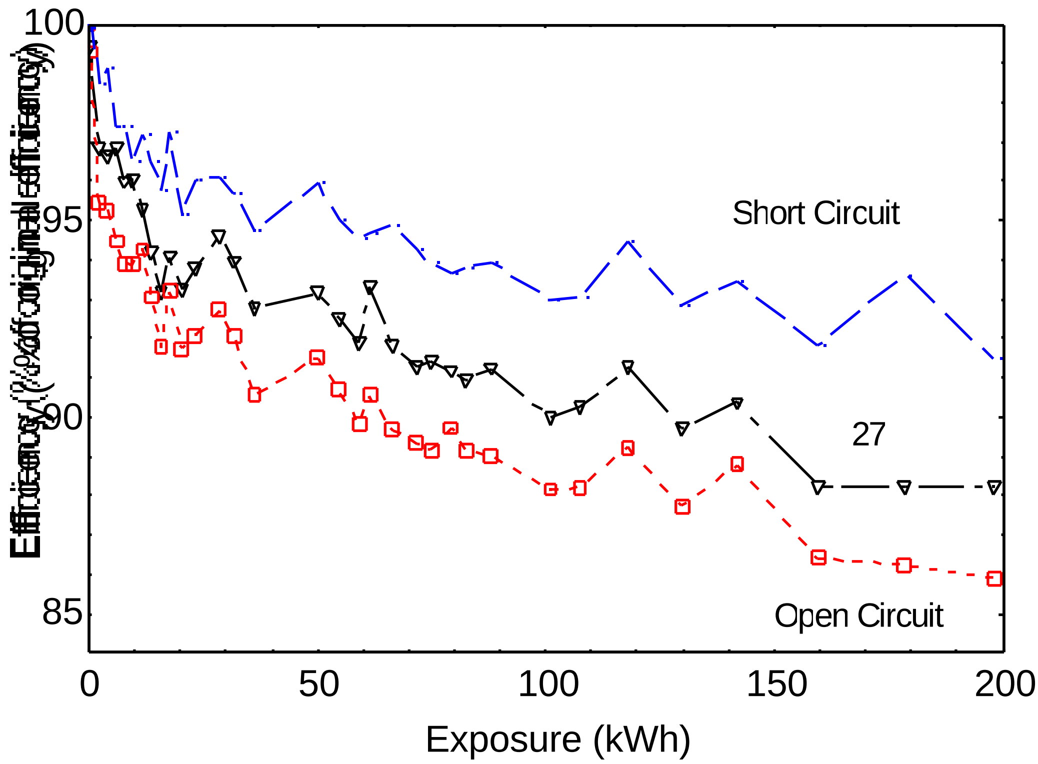

Figure 3: Measured efficiency versus time profiles for triple junction a-Si:H solar cell modules exposed to illumination in the field whilst connected to different loads.

In order to study the effect of different loads on the outdoor performance and long term stability of triple junction modules three commercially produced state-of-the-art triple junction a-Si:H solar cell modules were operated under different load conditions in outdoor conditions. The USSC US-11 a-Si:H triple junction solar cell modules were rated at 10 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 27 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 wired in short circuit configuration. Figure 3 shows the efficiency with time for the modules operating under the three different external loads. The measured outputs from the three test modules have been scaled using the output from an unexposed reference cell in order to account for any differences due to the measurement system.

Figure 3 again shows clearly that the load under which an a-Si:H solar cell module is operated can affect the rate and degree of degradation of that module. Figure 3 shows that the module operated under open circuit conditions (largest resistance) had degraded the most (14%) after 200 hours. The module operated under a load corresponding to that of normal operation near the maximum power point showed less degradation (12%) after 200 hours. The module operating under closed circuit conditions however showed the least degradation with a degradation of only 8% after 200 hours. These results, in agreement with the results from the single junction modules, reinforce the suggestion that not only the climatic conditions, such as temperature, under which an a-Si:H module operates affect its degradation and long term performance, but so do the load conditions under which it is operated.

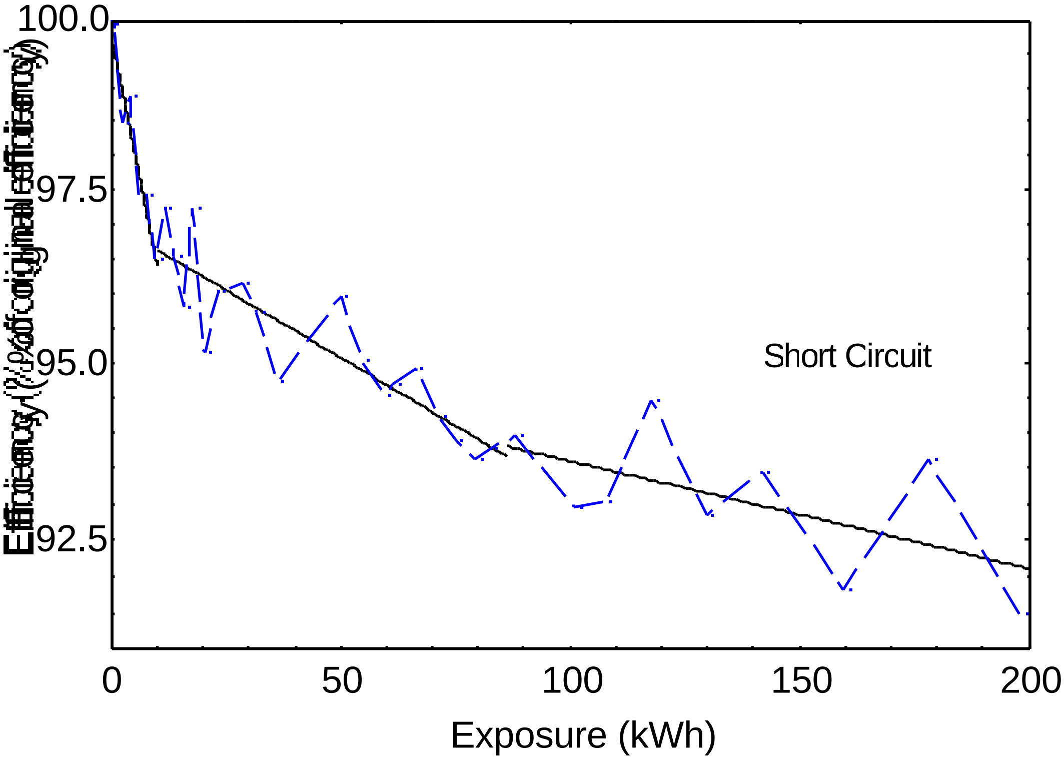

Figure 4: Degradation profile for a triple junction commercial *p-i-n* a-Si:H solar cell module operating in short circuit configuration exposed to sunlight in the field. Vertical axis is a log scale. A linear fit to the data is shown as a solid line.

Figure 4, shows the degradation data for the a-Si:H module in Figure 3 operated under short circuit conditions. This shows that the triple junction modules have a three-stage degradation profile, similar to that for the single junction modules. There is a rapid degradation in the first 10 hours, followed by a period of about 100 hours where the efficiency falls less rapidly. These two regions of rapid decay are then followed by a region of slower decay. This is the third region. At 200 hours the modules in Figure 4 are still in this third period of degradation, and have not quite reached their final stabilised values. A linear fit has been drawn in Figure 4, but if the normal pattern is followed this will develop in to an exponential decrease approaching an asymptote after about 300 hours.

CONCLUSIONS

Our results have shown that commercial single junction a-Si:H solar cells operated under open circuit conditions can degrade by up to 38%, compared to similar cells operated under maximum power point conditions which only degraded by an average of 14% after 13 days of field exposure. Similar studies of state-of-the-art triple junction a-Si:H solar cell modules have shown that triple junction cells operated under open circuit conditions can degrade by up to 14%, compared to similar cells operated at maximum power point conditions which only degraded by 12% after 200 hours of field exposure. Both of these modules however degraded more than a similar module operated at short circuit, which only degraded by 7% over the same period. It is clear from these field studies of commercial single and triple junction solar cell modules under different loads that not only do climatic conditions, such as temperature, affect the rate of degradation of a-Si:H modules, but so do the load conditions under which they are operated.

Our studies of both single junction and triple junction a-Si:H modules have also shown that both types of module appear to have a degradation profile with three distinct regions. The photovoltaic efficiency appears to fall very rapidly during the first 10 to 15 hours, losing from 10 to 35% of the relative efficiency for single junction cells and 3 to 8% for triple junction cells. This is followed by a period where the efficiency falls less rapidly for the next 60 to 100 hours of exposure to sunlight, losing up to a further 4 to 13% of the relative efficiency for single junction cells and 4 to 5% for triple junction cells. 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. Ultimate degradation rates can range from 14 to 38% for commercial single junction solar cell modules and from 7 to 15 % for triple junction modules, depending on how they are operated. This is in good agreement with the accepted results in the published literature which show that degradation can range up to 30% for single junction devices and from 10 to 20% for triple junction devices.

From our studies we recommend that a-Si:H modules whilst under illumination, and when not generating power at their maximum power point, should always be placed under short circuit conditions. They should never be exposed to illumination whilst under open circuit conditions. This means that currently used charge controllers that simply switch the module to open-circuit when the batteries are full should be modified to switch the module to short circuit or a low resistance load. A-Si:H modules should also always be delivered and assembled either in the dark, or under short circuit conditions.

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