Performance of an Amorphous Silicon Mini Module in the Initial, Light-Induced Degraded and Annealed States

M. Bliss*, J. Zhu, T.R. Betts, R. Gottschalg
Centre for Renewable Energy Systems Technology (CREST), Department of Electronic and Electrical Eng., Loughborough University, Loughborough, Leicestershire, LE11 3TU, UK
Tel.: +44 1509 635327, Fax: +44 1509 635301, Email: M.Bliss@lboro.ac.uk
*Corresponding Author

Abstract

This work analyses the performance of single junction amorphous silicon (a-Si) mini modules in three main states: the initial non-degraded state, degraded state after light soaking and recovered state after thermal annealing. The applied methods of controlled indoor light-soaking and thermal annealing are detailed. Performance measurements are carried out under varying spectrum (E), light intensity (G) and temperature (T). Results show a reduction in STC power of up to 27.5% during the first 250h light soaking and a recovery of 56% after annealing for 250h at 80°C in the dark. After light soaking, devices also showed a reduction in low light performance and an increase in temperature coefficients, which was partly reversed after annealing.

1 Introduction

Accurate prediction of the energy yield of amorphous silicon devices has proven to be very difficult because the PV device technology shows significant initial degradation [1] and strong seasonal variations in performance [2]. The effects have three main driving factors. The first two are high light intensity that causes a reduction in performance (Staebler-Wronski effect [3]) and high operation temperatures that cause thermal annealing, an effect that recovers some of the lost performance. During low temperature winter months a-Si devices lose performance because the effect of light induced degradation is dominant. In summer, the opposite takes place and the device recovers from light induced degradation because of much higher operating temperatures. The third factor that has to be considered for seasonal variations in performance is change in the sunlight spectrum. A-Si devices perform better at low air mass spectra in summer and worse in the winter months with on average more red-rich, high air mass spectra.

The initial loss in performance and the seasonal variations of a-Si devices depend on the location, operating conditions and the device structure. However, to date little conclusive research exists on how they interlink. Separating these effects from measured outdoor data is difficult as all environmental factors change continuously and influencing factors are superimposed and often correlated. Nevertheless, an understanding of the contributing factors is an important step to improve energy yield models and prediction.

To gain a better understanding of the performance variations of a-Si devices the performance of three mini modules is compared in their three main states: initial state, light-induced degraded state and recovered state after thermal annealing.

2 Experimental

Three commercially available a-Si mini modules have been tested in this work. The devices have a size of 50x47mm^2 and consist of 3 series connected cells.

Light-soaking of the a-Si devices has been carried out in a purpose built test rig with three separate sections. The first two sections (Ha1 and Ha2) use halogen light sources at different intensities and the third section (LED) uses white LEDs. A calibrated silicon diode in each section was used to monitor the light intensity and a T-type thermocouple positioned under each device was used to monitor the operating temperature. The complete rig was positioned in an environmental chamber controlled at 25°C air temperature. Light-soaking was carried out for 250h with the devices operating at open circuit. The operating conditions of the a-Si mini modules during light-soaking are detailed in Table 1.

Thermal annealing was carried out at 80°C under dark conditions for 250h at open circuit load in an environmental chamber.

Sect.	Irrad. [W/m^2]	Rel. I_{SC} to STC	Device temp. [°C]
Ha1	1450 ±95	0.20	59 ±1
Ha2	2800 ±55	0.46	70 ±2
LED	114 ±3	0.22	37 ±1

Table 1: Operating conditions in each of the sections of the test rig during light-soaking; due to the difference in spectral output, the device's I_{SC} in the LED section was still ~10% higher than in the Ha1 section.

Performance measurements under varying G-T-E have been carried out using the LED-based solar simulator prototype developed at CREST [4]. The system utilises 8 different LED colours to cover the light spectrum from ultraviolet to red and halogen light sources to cover the infrared part. A flexible spectral output and light intensity control is achieved with an independent light intensity control of each colour. A peltier based cooler/heater is utilised to control the temperature of the test device.

To allow comparison, the performance of all three devices has been measured under the same conditions in all three states (initial, degraded and annealed state). The applied measurement method for performance measurements at varying G, T and E is described in [5]. Device characteristics have been measured in a 3D matrix with 144 points under following conditions (see also Figure 1):

- 4 output spectra (best match to AM 1.5, AM 2, AM 4 and AM 6 see Figure 2)
- 9 intensities between 5% and 100% of maximum irradiance possible
- 4 device operating temperatures ranging from 15°C to 45°C in 10°C steps

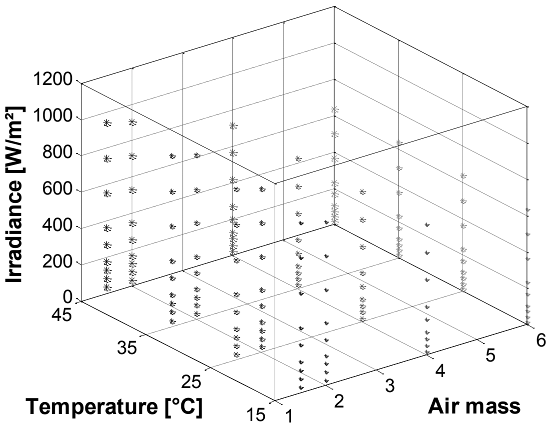

Figure 1: 3D illustration of device performance measurement points

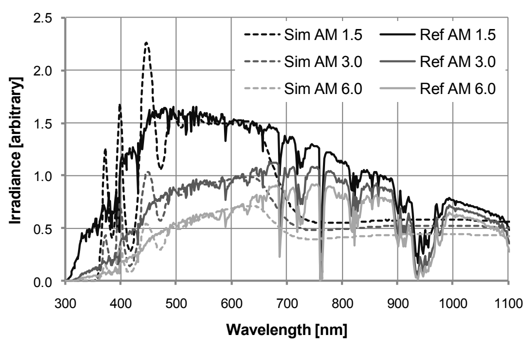

Figure 2: LED-based solar simulator output spectra compared to the reference spectra

Spectral response (SR) of the devices was measured using a dual-lamp filter based spectral response measurement system [6]. Measurements were carried out at ~0.1 suns background illumination from LED bias light. Results have been calibrated against the SR of a reference cell.

Power at STC was measured with a Pasan solar simulator to determine the change in performance due to the light soaking and annealing process.

3 Results and discussion

From Table 2 and Figure 3 it is apparent that a major part of the losses in performance of the a-Si devices during light soaking are due to a reduction in the fill factor (FF) and I_{SC} (photocurrent). The effect on V_{OC} is small in comparison.

Par.	Halogen 1	Halogen 2	White LED
After 250h light soaking:			
I_{SC}	-4.32%	-6.92%	-8.83%
V_{OC}	-1.53%	-2.55%	-3.70%
FF	-9.52%	-11.70%	-17.42%
P_{MP}	-14.76%	-19.91%	-27.50%
After 250h annealing at 80°C:			
I_{SC}	-2.46%	-4.39%	-3.43%
V_{OC}	-0.08%	-0.75%	-1.19%
FF	-4.29%	-5.36%	-7.90%
P_{MP}	-6.72%	-10.19%	-12.12%

Table 2: Relative deviation in the inital STC parameters after light soaking and annealing

The a-Si device light soaked under white LED light lost most in performance. At this point it is not known if this is due to the lower operating temperatures (less annealing) or differences in spectral output between the halogen and LED light sources or, most possibly, a combined effect. Interesting to note is that the performance loss of the device in the Ha2 section was higher than in the Ha1 section. One explanation might be that the relative increase in the light induced degradation effect between the Ha1 and Ha2 section was larger than the increase in the thermal annealing recovery effect.

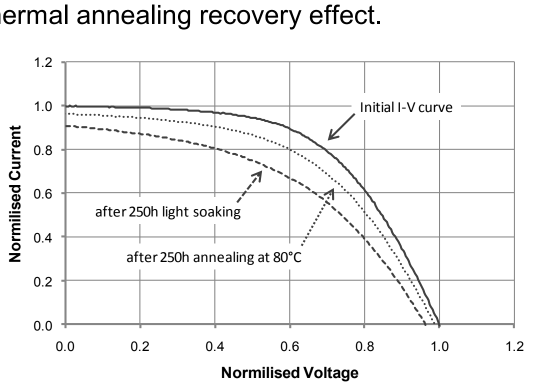

Figure 3: Comparison of the I-V curves at STC of the a-Si device in the LED section

The recovery in P_{MP} due to the annealing process was highest for the device in the LED section (56%) and lowest for the device positioned in the Ha2 section (49%). The recovery of the device in section Ha1 was similar to the LED section (54%). The smaller recovery in section Ha2 could be due to two reasons: -1- the device was already operating at high temperatures during light soaking so the effect of annealing could have been lower and/or -2- the irreversible degradation of the device was stronger due to the increased light intensity.

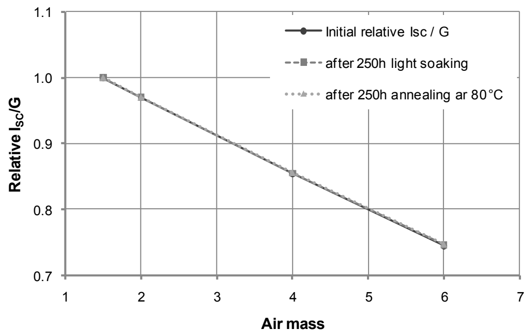

Figure 4: Comparison of the relative I_{SC} over G curves of the device in the LED section

It is apparent from Figure 4 that I_{SC}/G behaviour of the a-Si devices is significantly affected by spectrum. Increasing air mass results in a large drop in I_{SC}/G of the a-Si device. This is due to its SR being in the in the ultraviolet to red (~300-750nm) region where the sunlight spectra (and simulator light spectra) decreases the most with air mass. However, all devices have shown no change in this behaviour after light soaking and annealing. The SR of the all devices changed mainly in the absolute scale. Insignificant changes were found when comparing the relative SR (Figure 5).

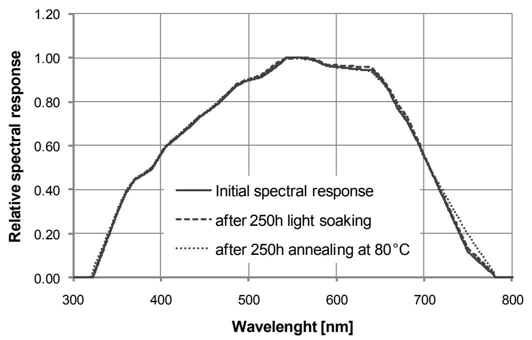

Figure 5: Relative spectral response of the a-Si device light soaked in the LED section

Changes in the I_{SC}/G behaviour have a direct influence on the device efficiency. However, as apparent from Figure 6, light soaking also reduced the relative efficiency at low light conditions. This was observed on all devices and was due to a reduction in the FF as illustrated in Figure 7. Thus, the detrimental effect of light soaking had a greater impact on the performance under low light conditions than at STC ($1000W/m^2$). In other words, the a-Si device from the LED section lost 27.5% at STC in P_M and 32.9% at $190W/m^2$. This additional loss has a large impact on performance at low irradiance and further reduces the energy yield in the winter months and in cloudy conditions. The performance recovery in P_{MP} at this intensity was with 58% slightly larger than at STC for the device in the LED section. However, the recovery was lower than at STC (45%) on the Ha2 device and unchanged on the Ha1 device.

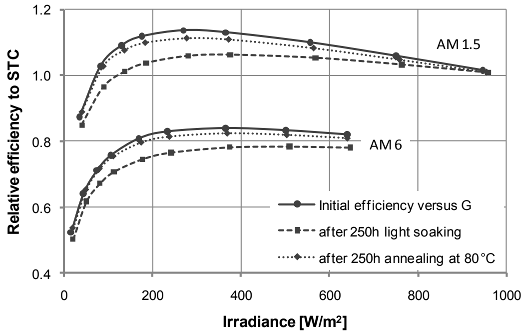

Figure 6: Relative efficiency curve of the LED section a-Si device at AM 1.5 and AM 6

All a-Si devices test have also shown a spectral effect on the FF (see Figure 7). The FF is benefitting from blue rich, low air mass spectra. After light soaking, an increase in the spectral effect was observed on all devices. Annealing had a reverse effect on the Ha1 and Ha2 device but showed a further increase for the device light soaked under white LED light.

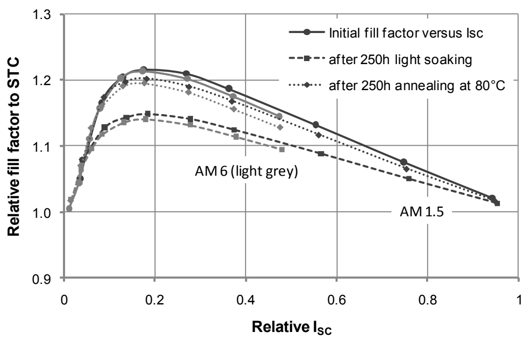

Figure 7: Relative fill factor versus I_{SC} at AM 1.5 and AM 6 of the a-Si device light soaked under white LED light

The temperature coefficients of the I-V parameters versus light intensity are illustrated in Figure 8 for the a-Si device light soaked under white LED light. It is noticed that the temperature coefficient in P_{MP} of this device in its initial state is ~5 times larger at low light conditions than at high irradiance. This is due to a more positive FF with increasing irradiance (not shown). The initial temperature coefficients of

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P_{MP} and FF particularly, varied to a large degree between the devices.

On all devices a significant increase in the absolute temperature coefficients of I_{SC}, V_{OC} and P_{MP} has been observed after light soaking. This was partly reversed through the annealing process on the devices in the Ha1 and LED sections. However, the device from the Ha2 section showed a small increase in the absolute temperature coefficient of P_{MP}, while the temperature effects on I_{SC} and V_{OC} where reduced as on the Ha1 and LED device.

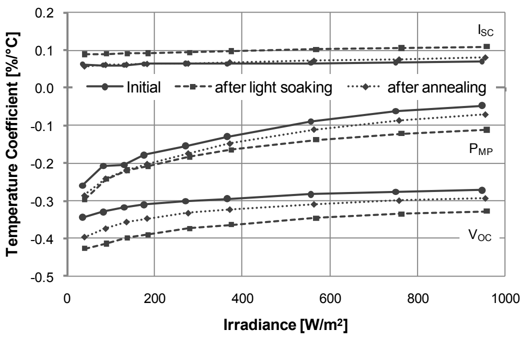

Figure 8: Temperature coefficients versus Irradiance of the a-Si device in the LED section; extracted from G-T-E matrix over the range 15°C to 45°C, relative to 25°C

Plotting the temperature coefficients of the a-Si devices against temperature itself (Figure 9) it is noticed that they vary significantly and increase with rising temperature. The a-Si device that was light soaked in the LED section showed a positive temperature coefficient below ~22.5°C in its initial state. The other devices tested stayed negative over the complete range investigated, but showed the same trend. The effect of light soaking and annealing seems to offset the temperature coefficients over the measured range, while light soaking increases the negative coefficient in P_{MP} and annealing partly reverses the effect (except in P_{MP} on Ha2). The amount of "offset" varied considerably between the devices.

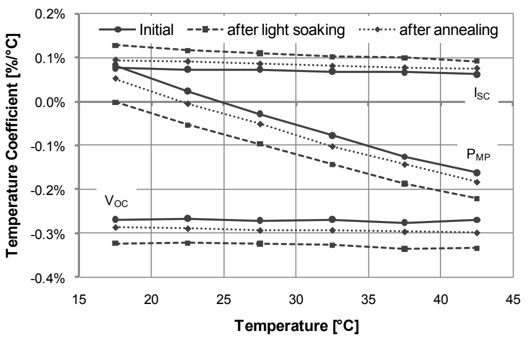

Figure 9: Temperature coefficients versus temperature at ~950W/m^2 and AM 1.5 spectrum of the a-Si device in the LED section

4 Conclusions and future work

This work has demonstrated first performance measurement results at varying irradiance spectrum, light intensity and operating temperature of a-Si single junction devices in their initial state, after 250h light soaking and in their recovered state after 250h annealing at 80°C.

Results show a large spectral effect in I_{SC} and FF that coincides with reported seasonal variations. The performance loss due to light soaking under white LED light and low operating temperature was significantly larger than under halogen light with high operating temperatures. Furthermore, the recovery during annealing was the highest in the LED case. Light soaking and annealing showed a large influence on all performance indicators except spectral response. Only a minor increase in the spectral effects on the FF was observed which was not reversed on all devices through annealing.

At this early stage of the project it is already possible to see how the three factors (spectrum, light soaking and annealing) effect seasonal variations and how they depend on the climate they are installed in. In the next steps, light soaking and annealing will be carried out on larger sample numbers under more controlled conditions for longer periods. Additionally, different light sources will be tested to investigate possible spectral dependence on light soaking. From this, a more detailed performance model will be developed that helps predict the performance variations to enable a more accurate energy yield prediction.

Acknowledgements

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