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PERFORMANCE OF AMORPHOUS SILICON IN THE INITIAL, DEGRADED AND ANNEALED STATES UNDER VARYING SPECTRUM, IRRADIANCE AND TEMPERATURE

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ABSTRACT: This work analyses and discusses the performance of amorphous silicon (a-Si) single junction mini modules in three main states: in the initial non-degraded, as purchased state, in the degraded state after light-soaking and in the recovered state after thermal annealing. The experimental set-up and applied methods of controlled indoor light-soaking and thermal annealing are detailed. Device performance measurements are carried out indoors under varying spectrum (E), light intensity (G) and temperature (T). Measurement results have shown a reduction in STC power of up to 27.5% during the first 250h light soaking and a recovery of 56% of the performance losses 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 to some extent reversed during the annealing process.

KEYWORDS: Amorphous Silicon, a-Si, Degradation, Annealing, Light-Soaking

1 INTRODUCTION

Accurate prediction of the energy yield of amorphous silicon PV devices has proven difficult because the technology shows significant initial degradation and strong seasonal variations in performance [1-3]. These changes in device operating performance are caused by three main driving factors: The first is high incident light intensity, which causes a light-induced degradation mechanism in the semiconductor material properties and thus a loss in device performance. The second factor is high device operating temperatures that enable thermal annealing, which is a performance recovery effect from light induced degradation that reverses changes in the semiconductor material properties. This phenomenon was observed by Staebler and Wronski [4] and is also referred to as Staebler-Wronski effect. Seasonal variations in a-Si devices can thus be explained as follows: during winter months a-Si devices lose performance because the effect of light induced degradation is dominant to the effect of annealing due to low operating temperatures. In summer, the opposite takes place and the device recovers from light induced degradation because of much higher operating temperatures and thus stronger annealing. However, a third factor that needs to be considered is the change in the sunlight spectrum over the seasons [5]. A-Si devices perform significantly better at low air mass spectra in summer and worse in the winter months with on average more red-rich, high air mass spectrum, also shown in this paper.

The degree of initial degradation and seasonal variation of a-Si devices is dependent on the device type/structure, on the location in which the device is operating and its operating history, which makes it difficult to predict device behaviour. Additionally, separating these effects from measured outdoor data is further complicated because environmental factors change continuously, are super-imposed and are often correlated with each other as such as light intensity and operating temperature. The objective of this project is thus to gain a better understanding of the performance variations and its influencing factors by means of indoor device performance measurements and controlled indoor operating conditions during light-soaking and annealing tests. With this understanding, the aim is to improve energy yield models and reduce energy prediction uncertainty of a-Si devices.

To gain further knowledge of the performance variations of a-Si devices, this work compares the performance of three mini modules in their three main states: initial state, light-induced degraded state and recovered state after thermal annealing.

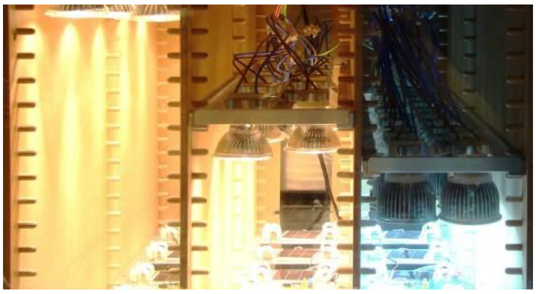
2 EXPERIMENTAL

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

2.1 Light-soaking and annealing

Light-soaking of the a-Si devices has been carried out in a purpose built test rig with three separate sections (see **Figure 1**). 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 I**.



Section 1 – Ha1 Halogen | Section 2 – Ha2 Halogen | Section 3 - LED White LEDs

Figure 1: Light-soaking chamber

Table I: 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.

Section	Irradiance [W/m^2]	Relative I_{SC} to STC	Device temperature [°C]
Ha1	1450 ±95	0.20	59 ±1
Ha2	2800 ±55	0.46	70 ±2
LED	114 ±3	0.22	37 ±1

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

2.2 Performance measurements

Power rating at standard test conditions (STC) of all devices has been measured with a Pasan solar simulator.

Performance measurements under varying spectral irradiance (E), light intensity (G) and device operating temperature (T) were performed using the LED-based solar simulator prototype developed at CREST [6]. 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 source 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 method for performance measurements at varying G, T and E is described in [7]. Device characteristics have been determined in a G-T-E matrix with 144 points under the following conditions (see also **Figure 2**):

- 4 output spectra (best match to AM 1.5, AM 2, AM 4 and AM 6 see **Figure 3**)
- 9 intensities between 5% and 100% of maximum irradiance possible under the given spectrum
- 4 device operating temperatures ranging from 15°C to 45°C in steps of 10°C

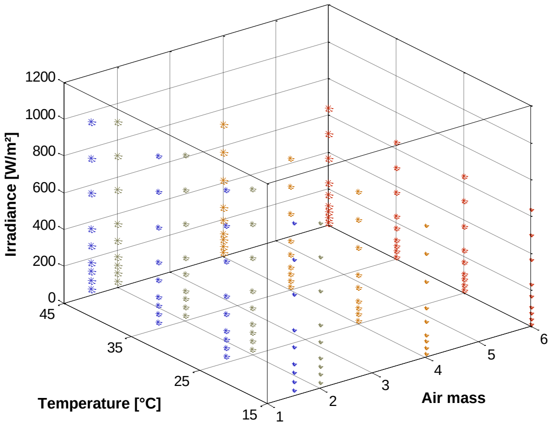


Figure 2: 3D illustration of device performance measurement points

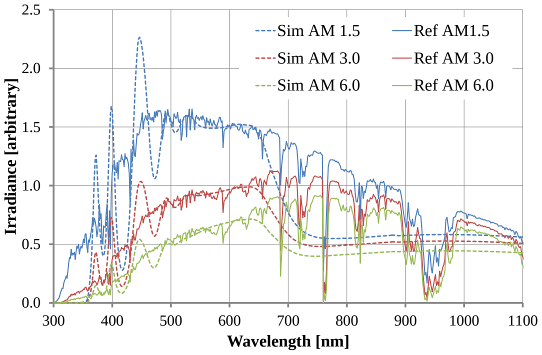


Figure 3: LED-based solar simulator output spectra compared to the reference spectra; the spectral match between simulator light and sunlight spectrum was on all spectra class B.

The spectral response (SR) of the devices was measured using a dual-lamp filter based spectral response measurement system. Further details can be found in [8]. Measurements were carried out at ~0.1 suns background illumination from LED bias light. Results have been comparison calibrated against the SR of a reference cell.

3 RESULTS AND DISCUSSIONS

3.1 STC performance

From **Table II** and **Figure 4** 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 effects on V_{OC} are relatively small in comparison. The losses are due to changes in the semiconductor material properties that resulted in a reduction in photocurrent and shunt resistance and an increase in series resistance of the devices.

Table II: Changes in performance to the inital STC parameters of all devices after light soaking and the relative recovery from the losses during annealing

Parameter	Ha1	Ha2	LED
Performance loss 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%
Recovery from loss after 250h annealing at 80°C:			
I_{SC}	43.02%	36.57%	61.15%
V_{OC}	94.77%	70.70%	67.82%
FF	54.97%	54.22%	54.64%
P_{MP}	54.48%	48.82%	55.92%

The a-Si device light soaked under white LED light lost most in performance. The effective irradiance between the LED and the Ha1 device differed only ~10% (**Table II**), yet the device light-soaked in the LED section lost nearly twice as much in maximum power. This is mainly due to differences is the operating temperature as it was 22°C cooler in the LED section and thus the recovery rate from annealing was much smaller. Nevertheless, a secondary effect might have been induced by using different light sources with significant differences in spectral irradiance during light soaking. However, with the current measurements it is not possible to determine the extent of spectral influences.

Interesting to note is that the performance loss of the device in the Ha2 section was ~35% higher than in the Ha1 section. The effective irradiance on the Ha2 device was more than twice as high as on the Ha1 device, while the Ha2 was operating only ~11°C warmer. Thus, one can argue that the relative increase in the light induced degradation between the Ha1 and Ha2 section was larger than the increase in the recovery due to elevated operating temperatures.

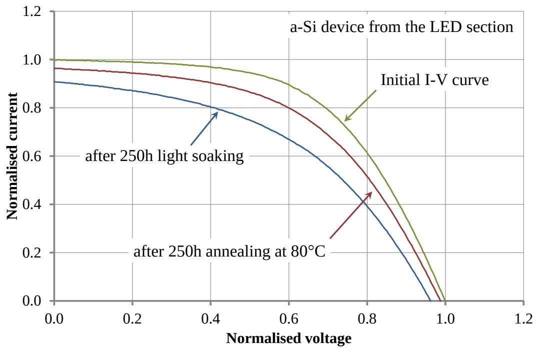


Figure 4: Comparison of the I-V curves at STC of the a-Si device in the LED section

The recovery in P_{MP} due to the annealing process was highest for the device in the LED section (56%), lowest for the device positioned in the Ha2 section (49%) and similar between the device in the LED section and Ha1 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.

3.2 Spectral response

All a-Si devices have shown insignificant changes in the relative SR after light-soaking and annealing (see **Figure 5** for the device in the LED section). Changes in I_{SC} (and photocurrent) of the devices are due to an absolute change in SR. This change in photocurrent is thought to be due to a reduction in carrier-lifetime and thus an increase in recombination. This aspect is currently being further investigated.

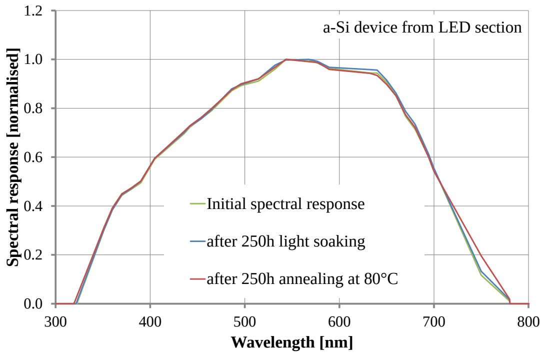


Figure 5: Relative spectral response of the a-Si device light soaked in the LED section

3.3 G-T-E performance

From **Figure 6** is apparent that the 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 the a-Si devices responding to the ultraviolet to red (~350-750nm) region (see previous **Figure 5**) where the sunlight spectra (and simulator light spectra, note **Figure 3**) decreases the most with air mass. As suggested from SR measurements, all devices have shown no change in this behaviour after light-soaking and annealing.

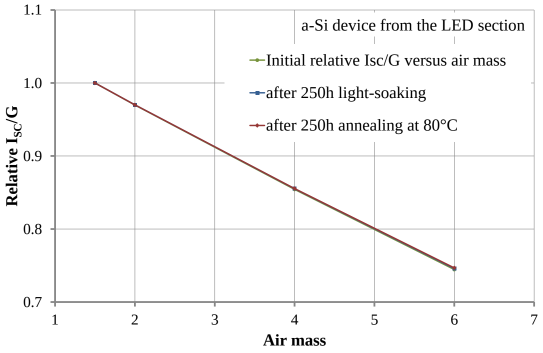


Figure 6: Comparison of the relative I_{SC} over G curves versus air mass of the device in the LED section

Nevertheless, the changes in the I_{SC}/G versus air mass behaviour have a direct influence on device efficiency (**Figure 7**) and thus power output. This change coincides with seasonal variations; performance is better at low air mass in summer and worse during the winter month with high air mass. For example, in a location such as Loughborough, UK the lowest air mass in summer (21st June) on midday is AM 1.1 and in winter the highest air mass seen is AM 4 at midday the 21st December. For the device from the LED section this translates to a performance difference of ~20% between the air mass at the summer high and winter low, which is a significant change that can account for a large proportion of seasonal variations.

As apparent from **Figure 7**, light soaking also reduced the relative efficiency at low light conditions. This was observed on all three devices and is a result of a reduction in the FF (see also **Figure 8**) that was mainly caused by a reduction in shunt resistance. 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_{MP} and 32.9% at 190W/m^2. This additional loss has an impact on performance at low irradiance and further reduces the energy yield in the winter months and in cloudy conditions. However, annealing has not shown on all devices a consistently higher performance recovery in P_{MP} at low light intensity, which suggests that this is more due to initial degradation. The recovery of the device in the LED section was with 58% slightly larger than for STC. The recovery was lower than at STC (45%) on the Ha2 device and unchanged on the Ha1 device.

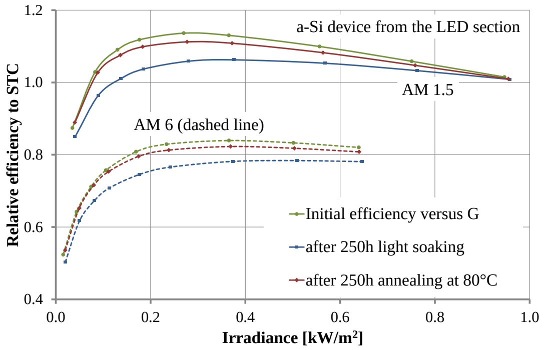


Figure 7: Relative efficiency curve of the LED section a-Si device at AM 1.5 and AM 6

All a-Si devices tested have also shown a spectral effect on the fill factor (FF) (see **Figure 8**), whereby the FF is benefitting from blue rich, low air mass spectra. This change in FF due to spectrum can further affect performance differences between the summer (higher P_{MP}) and winter (lower P_{MP}) season. Although this change in performance is significantly smaller than the change due to I_{SC}/G versus air mass, still it would measure an estimated 0.5% (AM 1.1 to AM 4) on the device in the LED section. After light soaking, a minor increase in this spectral effect was observed on all devices. A partially reversed effect was seen after annealing on the Ha1 and Ha2 device but a further increase was measured on the device light soaked under white LED light.

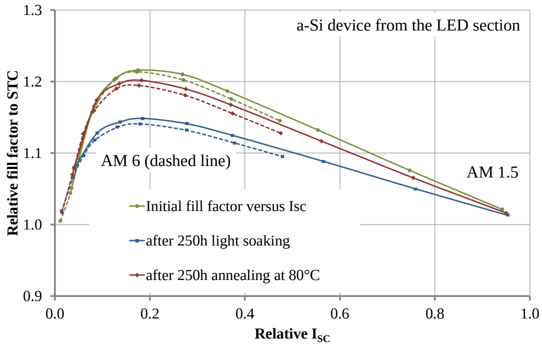


Figure 8: Relative fill factor versus I_{SC} at AM 1.5 and AM 6 of the a-Si device light soaked under white LED light

The temperature coefficients of the I-V parameters versus light intensity are illustrated in **Figure 9** for the a-Si device light soaked under white LED light. The initial temperature coefficients of P_{MP} and FF particularly varied to a large degree between the devices and lay in P_{MP} within -0.25% to -0.31% at low light conditions (5% rel. I_{SC}) and -0.05% to -0.16% at high irradiance (95% rel. I_{SC}). It is noticed that the temperature coefficient in P_{MP} of the device shown in **Figure 9** in its initial state is approximately 5 times larger at low light conditions than at high irradiance. This is due to a growing positive FF with increasing irradiance (not shown). However, the difference in P_{MP} coefficient was less significant on the Ha1 (~1.5) and Ha2 (~2.6) device.

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 after the annealing process on the devices in the Ha1 and LED section. However, the device from the Ha2 section did not show a reversed effect in the absolute temperature coefficient of P_{MP}, instead a small increase was measured, while the temperature effects on I_{SC} and V_{OC} were reduced as seen on the Ha1 and LED device.

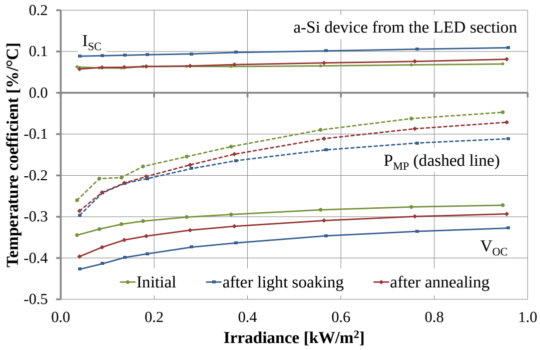


Figure 9: Temperature coefficients versus irradiance of the a-Si device in the LED section; extracted from G-T-E matrix over the range 15°C to 45°C, relative to 25°C

Plotting the temperature coefficients of the a-Si devices against temperature itself (**Figure 10**) 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.

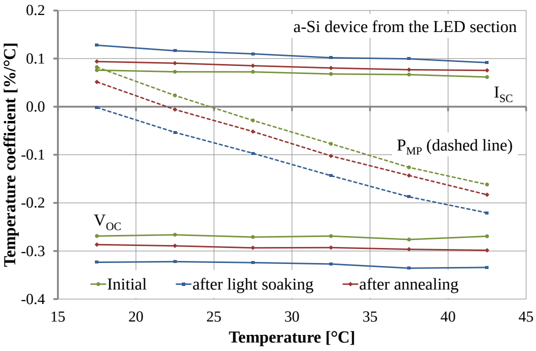


Figure 10: Temperature coefficients versus temperature at ~950W/m^2 and AM 1.5 spectrum of the a-Si device in the LED section

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 higher 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 relative spectral response. Only a minor increase in the spectral effect 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) affect seasonal variations and how they depend on the climate they are installed in. In the following steps, light soaking and annealing is 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.

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