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INVESTIGATION OF UV-INDUCED DEGRADATION OF DIFFERENT TYPES OF WPVS REFERENCE SOLAR CELLS

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ABSTRACT: Calibrated World Photovoltaic Scale (WPVS) reference solar cells are widely used for calibrating the irradiance of solar simulators as well as the determination of spectral mismatch correction factors. WPVS reference solar cells should provide long term stability of the short circuit current under standard test conditions < 0.3% over typical recalibration intervals of 1-2 years. The UV-irradiance of the utilized light sources (natural sunlight or solar simulators) can lead to degradation effects either in the solar cell itself or in the encapsulant. In this study different types of WPVS reference solar cells were exposed to elevated UV-irradiance in order to investigate the long term stability of the devices over a period of several hundreds of hours of permanent irradiation. Prior and after the UV-exposure high precision differential spectral responsivity (DSR) calibrations were performed in order to investigate the impact of the UV-aging on the spectral responsivity and hence the short circuit current of the individual devices. In order to identify small relative changes < 0.2% of the spectral responsivity a DSR-facility is needed with very high reproducibility. This could be realized at the DSR and Laser-DSR facilities at PTB.

Nine different types of reference solar cells were prepared by Fraunhofer ISE. They were developed to spectrally match different solar cell technologies. The BG38 and BG40 filtered devices should spectrally match a-Si solar cells, the OG590 and RG610 filtered devices should spectrally match µ-Si solar cells and the GaAs solar cell should spectrally match CdTe solar cells. The three unfiltered c-Si devices show different spectral responsivity in the IR-region. In conclusion these reference devices represent a thoroughly set covering all possible spectral responsivities needed in the PV-calibration and testing community.

Keywords: calibration, characterization, degradation, durability, encapsulation, radiation damage, reference cell, stability

1 INTRODUCTION

The comparability of different photovoltaic technologies and devices is maintained by the international standard IEC 60904 that defines the standard test condition (STC): irradiance E=1000W/m², AM1.5g spectrum and the device temperature of 25°C. If for some reason calibration or testing of photovoltaic devices of a given technology is intrinsically associated with large measurement uncertainties, generally problematic or even unreliable this might lead to a significant obstacle for a successful market entrance. Therefore, the development of measurement techniques for new photovoltaic technologies may be as important as the development of the technology itself.

For calibration and testing of photovoltaic devices solar simulators are generally used. For adjustment of the irradiance of the solar simulators to the demanded value of 1000W/m² calibrated reference devices are needed that are traceable to the SI-units.

Whenever the spectral responsivity of the device under test (DUT) differs significantly from the spectral responsivity of the reference device a spectral mismatch correction is needed for correcting the measured I_{STC} of the DUT. Generally, the uncertainty of the spectral mismatch correction factor increases with the deviation of the mismatch factor from unity. Hence a reference device that is spectrally matched to the DUT can lead to a significant reduction of measurement uncertainties.

However, the most important property of a reference device is the long term stability since recalibration intervals are often in the order of 1-2 years. If the short circuit current at standard test condition I_{STC} of the reference device changes significantly over time of use either shorter recalibration intervals are needed (that lead to extra costs) or the assigned uncertainty of the calibration value as to be increased over time until recalibration.

From experience with world photovoltaic scale (WPVS) reference devices encapsulated silicon solar cells have generally proven to be very stable. However, whenever new materials, encapsulants or solar cell technologies are incorporated into a new generation of reference devices the long term stability has to be investigated.

In this study we investigate the ultraviolet radiation (UV) induced degradation of different types of recently developed reference devices. UV radiation that occurs under real outdoor conditions but also when using solar simulators can be considered to be the most harmful. UV radiation might lead to reduced optical transmission in the encapsulants materials or defects within the semiconductor material. The degradation effect will be quantified by calibrating the reference devices prior and after enhanced UV-exposure using the differential spectral responsivity (DSR) facilities at PTB.

2 REFERENCE DEVICES

The set of reference devices was designed by Fraunhofer ISE to spectrally match the wide range of existing photovoltaic technologies (see Table 1) covering thin film technologies such as amorphous silicon, micro-crystalline silicon and CdTe as well as silicon technologies with different infrared sensitivity. Please note, that the reference device assignment A – I from

Table 1 will be used in the course of this paper when discussing the results. The spectral responsivity of these reference devices was measured by PTB and is shown in Figure 1 and clearly underlines the variety of the spectral matching.

Table 1: Reference devices

	Material	spectral match to
A	p-type c-Si + HOQ filter	c-Si/CIGS
B	p-type c-Si + cover glass	c-Si/CIGS
C	n-type c-Si + cover glass	c-Si/CIGS
D	c-Si + BG40 filter	a-Si
E	c-Si + BG38 filter	a-Si
F	c-Si + OG590 filter	µ-Si
G	c-Si + RG610 filter	µ-Si
H	GaAs	CdTe/CIS
I	GaAs + cover glass	CdTe/CIS

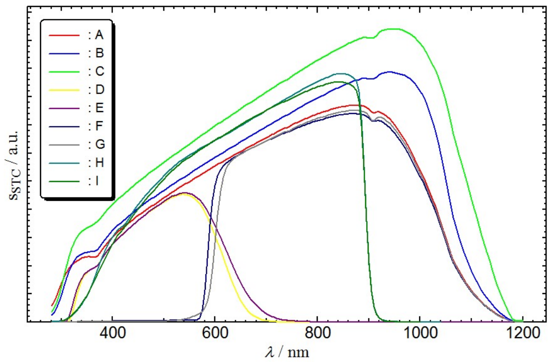

Figure 1: Spectral responsivity of the investigated reference devices. The assignment A-I can be found in Table 1.

3 EXPERIMENTAL

In this section we will describe the DSR facilities at PTB that were used for the spectral responsivity measurements, the UV-light source and finally the ageing procedure.

3.1 The DSR-facilities at PTB

The DSR facilities at PTB are primary calibration facilities that allow the calibration of reference solar cells with an expanded uncertainty of U(I_{STC}) < 0.6% for the lamp-based DSR facility and U(I_{STC}) < 0.4% for the laser-based DSR facility. At both facilities the absolute spectral irradiance responsivity at STC is measured. The I_{STC} is derived mathematically using the tabulated AM1.5g spectrum from the IEC60904-3 standard. Details about these facilities can be found elsewhere [1, 2].

However, the given uncertainties represent the absolute calibration of the I_{STC}. When it comes to ageing investigations only the relative change of the spectral responsivity and I_{STC} is discussed and statements of significance are wanted only for these changes. Therefore, all systematic uncertainty contribution that are related to the absolute value can be ignored for degradation investigations leaving only uncertainty contributions that contribute to the reproducibility of a measurement. For both facilities the reproducibility of measuring the I_{STC} of a reference device can be considered to be < 0.2%. This means that statements of significance can be made for observed ageing effect of a reference device > 0.2%. Less pronounced ageing effect cannot be stated to be significant since they also might result from the reproducibility of the measurement.

3.2 The UV-light source

For the enhanced UV-induces degradation two Labino UV-light sources were focused on the reference device. The spectral irradiance of the UV-source is shown in comparison the AM1.5g spectrum in Figure 2. It can be seen, that in the focus of the UV-sources the spectral irradiance about one order of magnitude larger that the AM1.5g spectrum. This enables enhanced UV-degradation investigations.

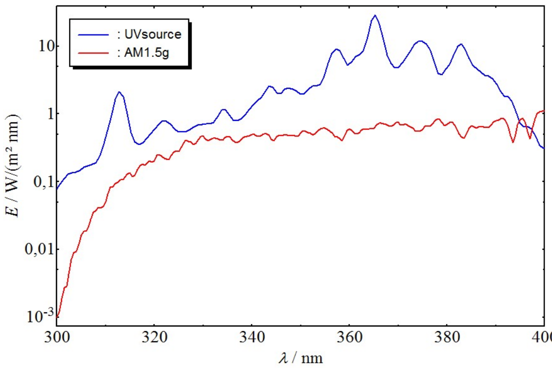

Figure 2: Comparison of the spectral irradiance of the Labino UV-light source and AM1.5g.

3.3 The degradation procedure

For investigation of the degradation the reference device is mounted on the automated sample stage of the DSR-facility. The UV-sources are mounted next to the DSR-facility optics, so that the sample stage can automatically move the reference device to the DSR measurement position as well as to the UV-exposure position in the focus of the UV-sources. It was carefully checked that there is no UV-exposure at the DSR measurement position. The degradation procedure of a reference device was performed as follows [3]:

(1) Complete absolute DSR-calibration
(2) Repeating degradation cycle
  a. Approx. 2h of UV exposure. The UV-irradiance induced current of the reference device is monitored.
  b. Measurement of the relative DSR at one given Bias-level

  This cycle is repeated up to 30 times.
(3) Complete absolute DSR-calibration

Additionally, a well characterized WPVS reference solar cell of PTB was calibrated together with the reference devices at step (1) and (3) in order to exclude drifting or other possible deviations of the DSR-facility over the several days of continuous operation. The calibration value of the PTB solar cell decreased by 0.1%. That is well inside the reproducibility of the facility.

By measuring the photocurrent during degradation, the in situ monitoring of the absolute UV-irradiance is possible. From step (1) the absolute spectral responsivity $s(\lambda)$ of the reference device is known. From (2a) the UV-induced current of the reference I_{UV} device is known at any time of the whole degradation procedure. Taking the relative spectral irradiance $E_{UV,rel}(\lambda)$, that were measured with a spectroradiometer, the absolute factor A of the spectral irradiance and hence the total UV-irradiance E_{UV} exposed to the reference device can be calculated at any moment during the degradation procedure:

$$I_{UV} = \int s(\lambda) \cdot A \cdot E_{UV,rel}(\lambda) d\lambda.$$

$$\Rightarrow A = \frac{I_{UV}}{\int s(\lambda) \cdot E_{UV,rel}(\lambda) d\lambda}$$

$$\Rightarrow E_{UV} = A \cdot \int E_{UV,rel}(\lambda) d\lambda$$

An example of this irradiance monitoring is shown with the red curve in Figure 3. The large step at the beginning shows the switching on of the second UV-source. It can be observed, that the UV-sources are not very stable, hence in situ irradiance monitoring is a reasonable choice for irradiance determination.

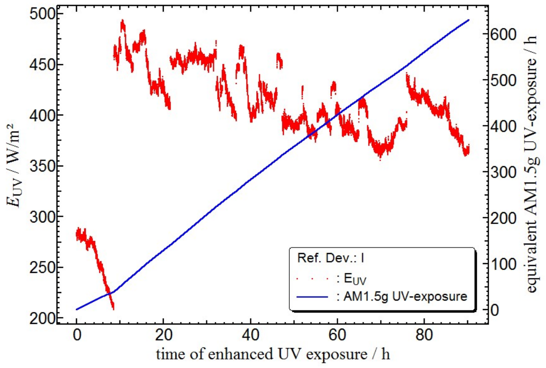

Figure 3: Monitoring the UV-irradiance during degradation by measuring the photocurrent.

The valuable information that can be derived from this data is the *equivalent AM1.5g UV-exposure*, which is an estimate of how many hours the solar cell has to be exposed to the UV-part (280nm – 410nm) of the AM1.5g spectrum in order to sustain an equivalent UV-damage comparable to the enhanced UV-degradation performed in the experiment. This value is estimated by multiplying the enhanced UV-exposure duration to the ratio of $E_{UV}/E_{AM1.5g,UV}$. This is exemplary shown as a blue graph in Figure 3. Please note, that this procedure cannot be applied to sample F and G, since these devices have negligible spectral responsivity in the UV-region. Hence an estimated value is given.

4 RESULTS AND DISCUSSION

The results of the UV-degradation experiments are summarized in Table 2 that shows the equivalent exposure time of the individual reference devices and the measured change of the I_{STC} after the UV-exposure. Please note, that the equivalent exposure time of reference device B, C and I are twice as long as the other devices. The exposure time can be considered to be rather high for a reference solar cell since reference devices are mostly illuminated for very short time periods when adjusting the irradiance level of a solar simulator.
The right hand side of Table 2 and Figure 4 denote the measured relative change of the short circuit I_{STC}. It can be observed that apart from device D and E all observed ageing effects are well within the reproducibility range of the facility. This reproducibility is underlined by the drop of 0.1% of the I_{STC} of the internal PTB reference that has not been exposed to UV-irradiation. Hence these reference devices can be considered to very stable.

Table 2: Impact of UV-degradation on short circuit current of the individual devices.

	Equivalent exposure / h	ΔI_{STC}
A	330	-0.18%
B	514	+0.13%
C	530	-0.01%
D	290	-0.35%
E	281	-0.46%
F	ca. 280	+0.11%
G	ca. 280	+0.15%
H	253	-0.15%
I	630	+0.06%
PTB	0	-0.10%

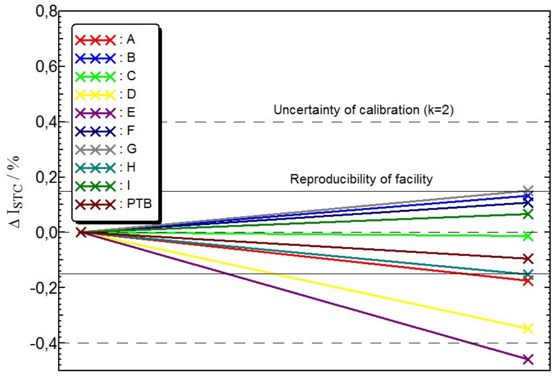

Figure 4: Change of I_{STC} due to UV-exposure

On the other the degradation of reference device D and E can be considered to be significant.
More insight in these changes is gained from the changes of the spectral responsivity that are shown in Figure 5. There it can be observed that the devices crystalline silicon and GaAs based devices B, C, H and I do not show any significant UV-degradation in the whole spectral range.
The HOQ-, BG40- and BG38 filtered devices A, D and E show a very similar and significant drop of the spectral responsivity below ≈ 500 nm. For all three devices this effect is in the same order of magnitude. Since the devices D and E are filtered in the infrared this leads to the significant drop in the I_{STC}. In contrast for the HOQ-filtered device A the impact of this change of spectral responsivity on the overall *relative* change current is of course much smaller.
The OG590 and RG610 filtered devices F and G show a very significant change in the spectral responsivity in the blocking region < 560 nm. There the spectral responsivity increases significantly after UV-exposure (please note the different percentage scale in these graphs). This indicates a degradation of the filters leading to a higher transmission and hence to a higher spectral responsivity and a higher current. However, since the degradation only occurs in the blocked spectral range the effect on the overall I_{STC} is only minor.

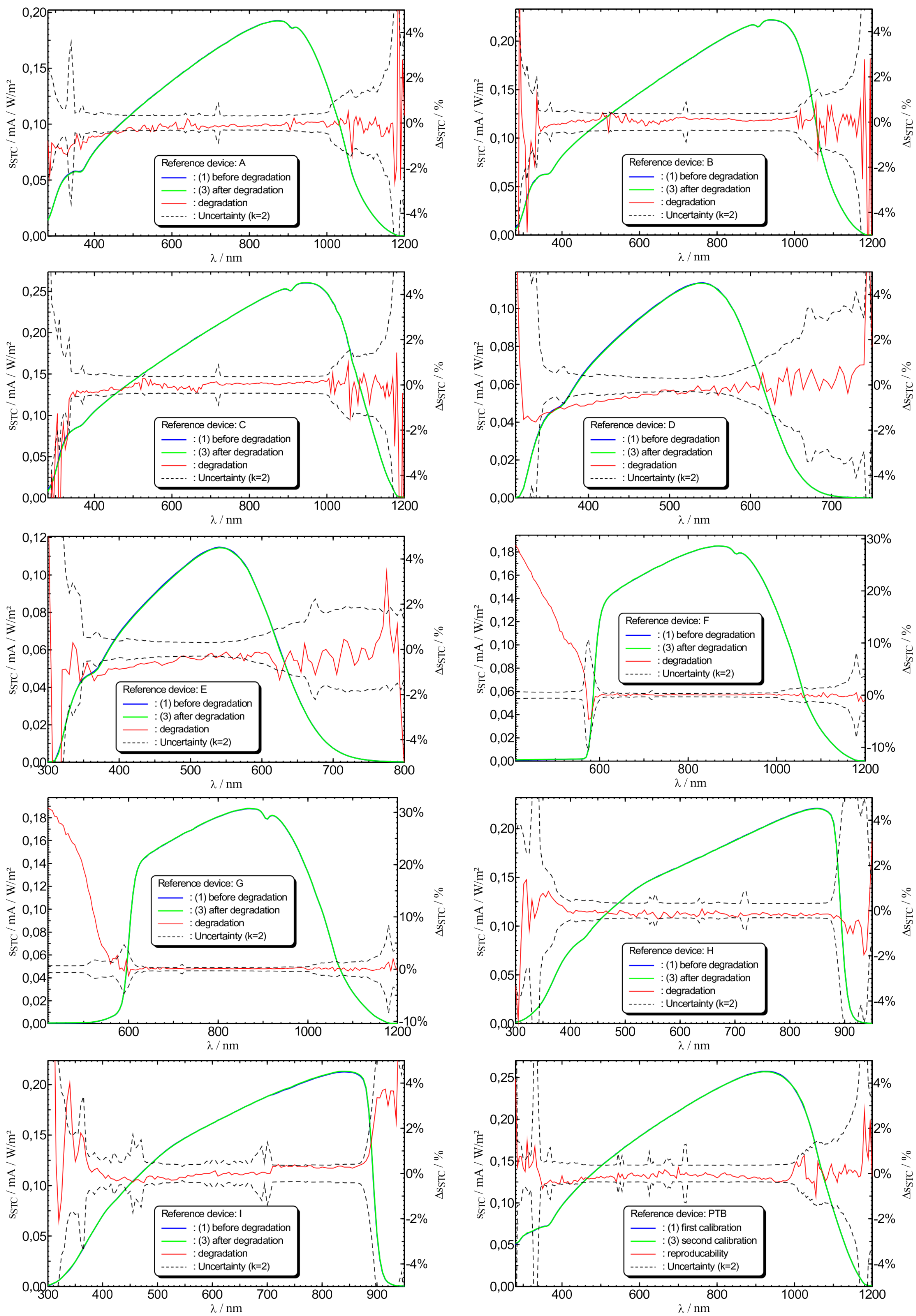

Figure 5: Changes of spectral responsivity due to UV-exposure.

5 SUMMARY

We investigated the UV-induced degradation of a variety of different (filtered) reference solar cells developed by Fraunhofer ISE. The measurements were performed by the high precision differential spectral responsivity facilities at PTB. The degradation was performed with enhanced UV irradiation with spectral irradiance between 280 nm – 410 nm. AM1.5g equivalent UV exposure durations between 250 hours up to 630 hours were achieved. Considering the spectral data, UV-degradation effects could be identified and the impact on the I_{STC} was discussed.

In summary, apart from the BG38 and BG40 filtered devices, the reference solar cells showed no significant degradation with respect to the I_{STC}.

6 ACKNOWLEDGEMENTS

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7 REFERENCES

[1] S. Winter et al, Proceedings. 16th European Photovoltaic Solar Energy Conf. (2000), 4ff
[2] S. Winter et al, Measurement 51 (2014), 457ff
[3] S. Winter et al, Proceedings. 22nd European Photovoltaic Solar Energy Conf. (2007)