FLASHER TOLERANCES OF POWER MEASUREMENT ON MICROMORPH TANDEM MODULES

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ABSTRACT: For the measurement of tandem cells under a sun simulator, the spectral mismatch correction of the short circuit current to the AM 1.5 standard spectrum cannot be calculated as for single junction cells. Therefore the power determination of multiple junction cells and modules underlies considerable additional uncertainties. The measurement tolerance depends not only on the spectrum of the sun simulator and the spectral response of the test and the reference cell, but also on the degree of the blocking ability of the tandem cell's limiting junction. In this work, the influence of the limiting junction on the spectral mismatch of sun simulator measurement of the power of tandem modules is studied as a function of their reverse currents. In consequence, the error bar is also a function of the individual tandem cell module under test, even if the spectral responses were assumed as fixed. In this paper a µ-morph tandem cell is modelled with two filtered crystalline cells. An upper limit for the additional error bar from the tandem problem is estimated on the basis of the given spectral quality of the sun simulator spectrum and the reverse current characteristics of the module.

Keywords: micromorph silicon cells, spectral mismatch, sun simulator

1 INTRODUCTION

The measurement of tandem and triple junction solar cells is loaded with an extra uncertainty over single junction cells through their more complex spectral mismatch. Figure 1 shows a deviation of +/-4% between laboratories involved in the IP performance for the maximum power of µ-morph silicon tandem solar cells laboratories [1].

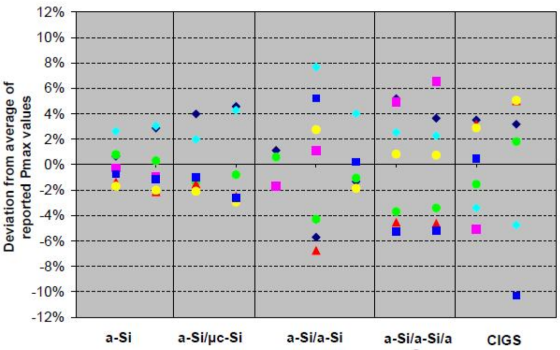

Figure 1: Comparison of the measurement results of different technologies of different module test laboratories [1].

For µ-morph tandem cells the spectral response depends on the thickness of each layer and the collection efficiencies of the top and the bottom cell, respectively. In Figure 2 two different µ-morph cells and a classical pure amorphous silicon tandem cell are shown.

The short circuit current measurement error depends on the spectrum of the sun simulator and the spectral responses of the tandem's top and bottom test cell, but also on the blocking ability of the limiting junction, i.e. the spectral mismatch can not be calculated according to IEC 60904-7:1998 Ed.2.

Beside the problem of the mismatch correction for the short circuit current, the correction to standard test condition of the maximum power point of the series connected top and bottom cell is even more complicated: the addition of two IV curves reveals a change in the fill factor as well [2]-[5]. Similar to series connected cells in crystalline cells, the fill factor goes up with an increasing current mismatch, while the short circuit current would decrease and the open circuit remains constant.

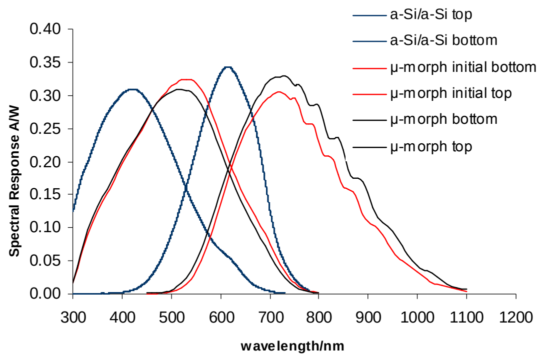

Figure 2: Spectral response measurements with bias illumination in the red and blue range for top and bottom cell, respectively, for two µ-morph tandem solar and an a-Si/a-Si cell.

In the end, a method for the tolerance evaluation of the power measurement of tandem cells is not developed yet, but a good guess from round robins test such as in Fig. 1. In this paper, the problem of the systematic uncertainty on the power measurement of µ-morph cells and modules is approached by the reverse current characteristics of the specific cell or module under test.

2 EXPERIMENTAL

To measure the dependence of the short circuit current by variation of the spectrum a LED sun simulator of STRAMA was used as light source.

The led simulator consists of 400 LEDs of 4 different types (white 400 nm - 750 nm, 740 nm, 850 nm, 950 nm) and fulfils the requirements of a class AAA simulator according to IEC 60904-9 Ed.2.0. The spectrum was recorded with an AVANTES spectrometer and spatial uniformity and temporal stability was confirmed to be class A for an illuminated area of 300mm x 300mm.

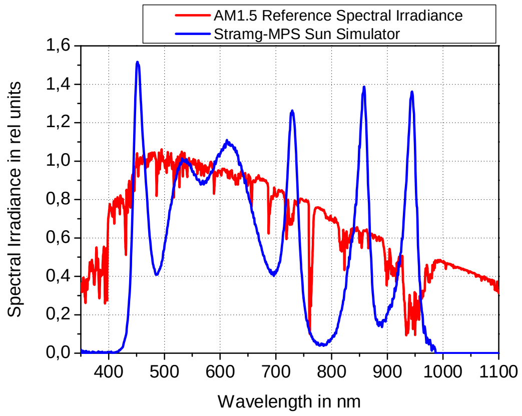

Figure 3: Spectrum of the 4-LED sun simulator from STRAMA in comparison with the AM 1.5 reference spectrum.

While changing the spectrum by the intensity ratios of the four LED types, the total irradiation intensity was kept constant at 1,000 W/m² with a pyranometer and a crystalline silicon cell monitoring using spectral mismatch correction. For measuring the IV-curve the electronic load of the PASAN 3SSb flasher was used (Class AAA on 3m x 3m illuminated area, spectrum quality see below).

The spectrum variation can be used to find the matching point of top to bottom cell and to monitor the power changes as a function of the current mismatch.

For the measurements different µ-morph tandem modules, which are bottom and top limiting and a model test cell, were used.

The model test cell consists of two crystalline cells with different filters to design a stable top and a stable bottom cell. The filter of the top is a KG 3 filter and for the bottom cell a combination of KG 2 and FG 13 filter was used.

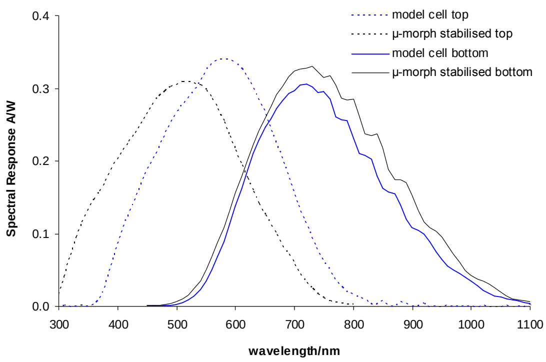

Figure 4: Spectral response of the crystalline silicon model tandem cell

Because of the EVA encapsulation of the crystalline cells the spectral response is limited to 360 nm for the modelled top cell in Fig. 4.

The current match of the model cell has been adjusted by partly shading of the cells at PI's PASAN 3SSb flasher until the current mismatch of both cells' reaches zero.

3 RESULTS

3.1 LED SIMULATOR

The match point of the crystalline model tandem cell under the LED spectrum is close to the math point under the spectrum of the flasher, although it shows a small red shift in Fig. 5. At the matching point, the short circuit current I_{sc} and the maximum power point P_{max} reach their maximum values. On the other hand, the fill factor *FF* is in its minimum at the match point, which is in line with similar measurements on III-V tandems cells in [2].

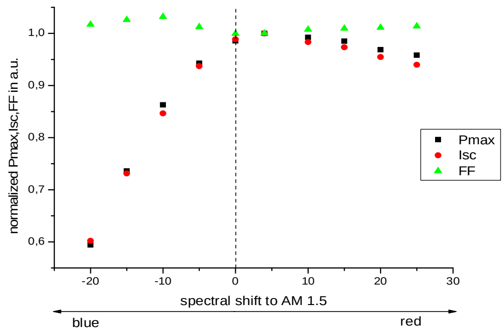

Figure 5: Change of IV curve parameters for the crystalline silicon model tandem cell by variation of the LED simulator spectrum. The match point is more reddish because it was adjusted under the Pasan flasher.

3.2 Dependence on shunt resistance

The decrease of I_{sc} and P_{max} from its maximum is much more pronounced for the blue shift than for the red shift of the spectra, see x axis in Fig. 5. This indicates already, that the reverse current is lower for the modelled top cell than for the bottom cell. This behaviour is still present when plotting the maximum power point against the current mismatch in Fig. 9 below.

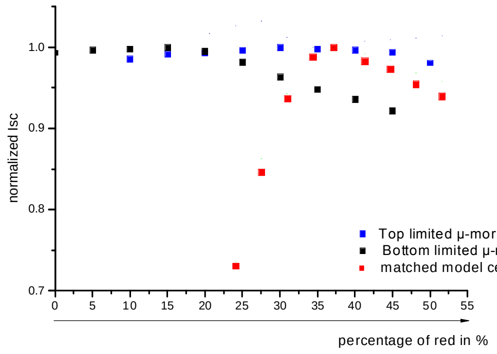

Figure 6: The crystalline model tandem cell vs. top and bottom limiting µ-morph tandem cells. From this figure one can conclude a lower error bar for the additional spectral mismatch error of µ-morph tandem cells, because of the higher reverse currents of the µ-morph cells

In Fig. 6. two µ-morph tandem solar mini-modules (10 cells, 10 cm x 10 cm), top and bottom limiting respectively, are compared with the crystalline model tandem cell. The decrease of the I_{sc} from its maximum is by more than one order higher for the crystalline model cell than for the two µ-morph tandems. This means, that the crystalline cell is much more sensible to spectral deviations from the standard spectrum or the spectrum corresponding to the match point, respectively, than the µ-morph cells. This can be attributed to higher reverse currents of both cells in the µ-morph tandem cells.

Fig. 5 shows the influence of the shunt resistance on the slope of the I_{sc} off the match point. By making use of the four terminal configuration of the model tandem cell, different ohmic resistances were connected in parallel to the top cell. This increases the top cell's reverse current, and flattens the slope of I_{sc}.

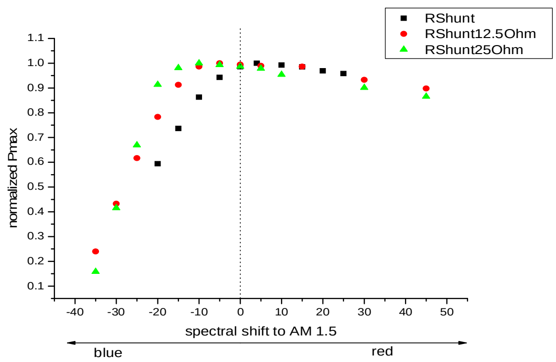

Figure 7: Maximum power P_{max} of the model tandem cell vs. spectral variation for different shunt resistances of the top cell. With decreasing shunt resistance the reverse current increases and the slope of P_{max} in the blue flattens.

4 ERROR ANALYSIS

There is a difference of circa 3% in the calculated current mismatch of all three tandem cells in Fig. 8. by comparing the current mismatch of top to bottom cell for the Pasan spectrum against the standard AM 1.5 spectrum. More general, the simulator at PI Berlin is slightly too red for the measurement of µ-morph cells. A similar deviation, even if not quantified, was already visible for the model tandem cell in Fig 3.

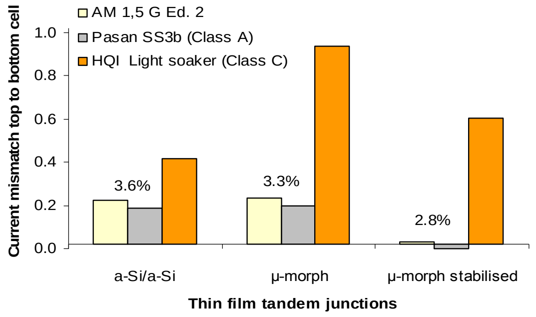

Figure 8: The current mismatch between top and bottom cell calculated from the spectral response given for the three tandem cell examples in Fig. 2. The current mismatch for the Pasan vs. standard AM 1.5 spectrum differs by 3%.

Thanks to the four terminal configuration of the model tandem cell, one can measure the actual mismatch of the model tandem cell for the spectrum variation at the LED simulator. In Fig. 9 the variation of P_{max} with the spectral shift of the LED simulator is plotted against the measured current mismatch. The 3% difference in the current mismatch from Fig. 8 is used to estimate a specific error bar of P_{max} for the specific tandem model cell (without additional shunts) at PIs' specific Pasan flasher.

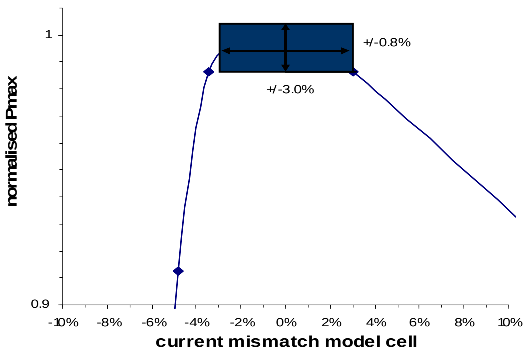

Figure 9: The deviation of the tandem current mismatch ±3% between PI Berlin's flasher Pasan 3SSb and the AM 1.5 standard spectrum from Fig. 7 converts to ±0.8% additional tolerance in Pmax for the crystalline model cell in Fig. 8. Because of the higher reverse currents of the µ-morph cells, this tolerance holds as an upper limit for µ-morph cells and modules as well

As the slopes of the IV curve parameters for the crystalline model cell are much steeper than those for the µ-morph cells the error bar of 0.8% from Fig. 9 holds as an upper limit for the additional error in the detailed error analysis for the power measurement of µ-morph cells and modules on a specific sun simulator. The flatter slopes are consistent with higher reverse currents due to the higher defect concentration and recombination rates in µ-morph thin film cells compared to crystalline cells.

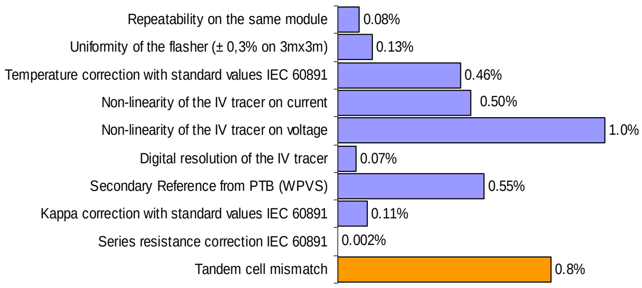

Figure 10: The detailed uncertainties in the power measurements of photovoltaic modules including an additional tandem cell mismatch for µ-morph modules at PI Berlin's specific sun simulator (Pasan SS3b from 2010)

The uncertainty of the P_{max} measurement for modules based on single junction cells (calibration performed with a secondary reference from PTB in WPVS design) leads to a combined expanded uncertainty of P_{max} of ± 2.8% for U95 (coverage factor k = 2) in the case of PI Berlin's laboratory configuration.

The actual spectrum deviation of Pasan 3SSb is according to IEC 60904-3 Ed. 2:

400–500nm: -5%

500–600nm: 1%

600–700nm: 6%

700–800nm: -1%

800–900nm: -3%

900–1100nm: 1%

Considering the determined µ-tandem cells uncertainty of ± 0.8%, from the spectral mismatch under PI Berlin's flasher, the combined expanded uncertainty of P_{max} results to be ±3.1% for U95 (coverage factor k = 2)

5 CONCLUSIONS

The calculation of mismatch factors for tandem cells is not a straight forward calculation as in the case of single junction cells because of the series interconnection of a top and a bottom cell with inherently different spectral responses.

The uncertainty of the P_{max} measurement for µ-morph tandem modules depends on the reverse current characteristic, i.e. the lower the reverse current is, the higher is the uncertainty. In other words, a less effective blocking of the limiting junction weakens the effect of spectral variations on the measured power of the tandem module.

An uncertainty of P_{max} of ±3.1% for U95 was calculated for µ-morph modules on the basis of spectral measurements with a 4-LED-Simulator at 1000 W/m² on a crystalline model cell. This model cell showed lower reverse currents than the µ-morph tandem cells, because of the higher recombination rates in µ-morph cells. In return, the tolerances, which were estimated from measurements on the crystalline model tandem cell were used as an upper limit for the error bar of the µ-morph modules. As long as there is no procedure for the spectral mismatch correction of tandem cells, sun simulators of higher spectral quality or outdoor measurements are the most effective tool to lower the measurement error on µ-morph tandem cells. In the meantime such sun simulators are commercially available even for larger sized modules.

REFERENCES

[1] Tony Sample "Thin Film Module Testing: State of the Art", 1st EPIA International Thin-Films conference(2008), http://2008.thinfilmconference.org/fileadmin/TFC_docs/PDF/081114_TFC_05_001_Sample.pdf

[2] M. Meusel et al., "Spectral Mismatch Correction and Spectrometric Characterization of Monolithic III–V Multi-junction Solar Cells", Prog. Photovolt: Res. Appl. (2002) p.243

[3] A. Nakajima et al., "Spectral Characteristics of Thin-Film Stacked-Tandem Solar Modules", Japanese Journal of Applied Physics Vol. 43, No. 10 (2004) p. 7296

[4] R. Adelheim K. Bücher., "Performance and parameter analysis of tandem solar cells using measurements at multiple spectral conditions", Solar Energy Materials and Solar Cells 50 (1998) p. 185

[5] A. Nakajima et al., "Optimization of Device Design for Thin-Film Stacked Tandem Solar Modules in Terms of Outdoor Performance", Japanese Journal of Applied Physics Vol. 43, No. 9A/B(2004) p. L 1162