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SPECTRAL RESPONSE MEASUREMENT OF TANDEM MODULES

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ABSTRACT: The measurement of the spectral photo current of stacked solar cells using semiconductor materials with a lower bandgap material as the bottom cell and a higher bandgap material as the top cell, like the a-Si/uc-Si tandem solar cell, is needed to conduct high accurate nominal power measurements. The prediction of the annual energy yield of tandem cell concepts also depends on the current matching of the top and bottom cell at standard STC spectra, not only on the STC nominal power. Thus the customers have to know if the optimal current matching is reached at STC AM 1.5 spectra or at a spectrum shifted more to the red or to the blue. The spectral photo current measurement is a standard on the small square centimeter cell area, especially in research labs, mostly using monochromatic light and colored bias light. In this paper we report the successful measurement results of the photocurrent of large area square meter sized tandem modules at wavelength between 400 and 1100nm using 50nm bandpass filters and blue and infrared LED bias light. Additionally a new measurement method is successfully introduced to measure changes of the short circuit current of a tandem modules using a dynamic changing LED bias light together with STC flasher light during a few milliseconds or without flasher light. Analyzing the characteristics of the measured tandem module current within a few milliseconds it can be clearly seen if the module is top or bottom limited, even the degree of mismatch is able to be characterized precisely. Thus the later analysis has the potential to be implemented as a standard measurement procedure within the end test of a tandem module production line. Even existing standard flasher may be adapted, without changing the existing flasher light source, by mounting the additional LED bias light source to perform different characteristics of dynamic bias light.

Keywords: module tests, photocurrent, spectrum, energy yield

1 INTRODUCTION

Sun spectrum is changing during the day and affecting the solar module performance relative to the rated STC AM 1.5 spectra. It is well known that at typical operation conditions during clear sky in the afternoon the spectrum is shifted to the red and more to the blue relative to AM 1.5 if the traveling distance of the sunlight through the atmosphere is short, like at noon in summer time.[1] Thus locations at lower latitude face a more blue shifted spectra, also strongly dependent on the local weather conditions, pollution and the height relative to the see level. Module technologies differ in their spectral response characteristics and those have to be measured to predict annually energy yield. Standard single band gap show smaller changes of the efficiency compared to multi band gap solar cell concepts, like the widely used tandem a-Si/μc-Si type.[2] On the cell level, measurement techniques are available for example by the use of a monochromator and different colors of bias light sources. They measure the spectral response characteristics individually for the top and the bottom cell within the tandem by applying either the red or the blue bias light.[3] On the module level such measurement systems are not widely available and not used in standard measurement procedures of tandem module production. Some measurement setups apply in principle the known cell spectral response techniques to a sector of several square centimeters of the module.[4] Up to now the customer only gets the value of the customers STC nominal power at the certain spectra of AM 1.5. Fig. 1 illustrates three examples of efficiency characteristics with changing spectrum, offering individually the same values of STC efficiency. Thus, especially for tandem concepts the market should be provided with the information of the spectrum where optimum matching of the two sub cells in the tandem module is reached.[5]

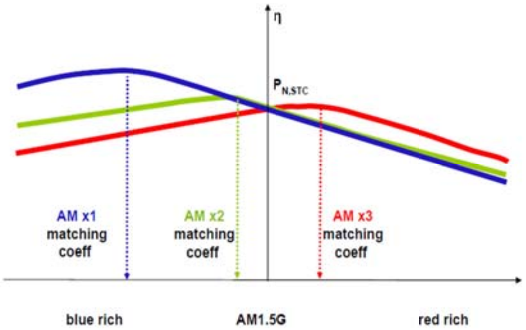

Figure 1: Schematic drawing of three tandem modules offering the same efficiency at STC AM 1.5 spectrum but differ significantly at other spectra’s due to their different matching of top and bottom cells. [5]

Spectral response characteristics of PV modules are used to predict the changes in the produced electrical power output as a function of the spectra even at STC nominal power measurements. The spectral characteristic of a PV module DUT Device under Test is needed, to correct the spectral mismatch of the used light source and thus reaching low final measurement uncertainty values of STC power measurements.[6] The measurement of spectral response of standard crystalline silicon modules and thin film CdTe and CIS modules have been demonstrated by the use of the SMFB Swiss Mobile Flasher Bus in recent publications.[7] In the present project the SMFB was equipped with a special developed bias light and the photocurrent measurement was applied to a 1.4m^2 a-Si/μc-Si modules.

The goal of this paper is to propose a measurement method, so that the tandem module manufacturer is able to highlight the present spectral matching factor on the data sheet.

Additionally a measurement method is proposed to measure the current matching factor, within the time of one simulator flash. This method has the potential to be integrated in the manufacturer's final nominal power test, without significantly increasing the length of the flasher test period in the line.

2 SPECTRAL RESPONSE MEASUREMENT SETUP

In July 2009 the Swiss Mobile Flasher Bus was constructed, by the integration of a commercial Pasan flasher [7] into a Mercedes Sprinter bus (Fig. 2). Since then several measurement tasks were performed under the responsibility of the EKZ with typically 50 to 200 modules tested a day right at the customer's site. (Fig. 1) The mobile test laboratory SMFB is able to perform flasher based nominal power measurements, spectral response measurements of single junction technology and low irradiance measurements all on module level.[8]

This uncertainty value of the nominal power measurement is about 1% larger than values of the best stationary test labs but enables still very accurate measurements at ambient temperature conditions with the advantage to make more measurements directly on customer's site.[9]

2.1 Standard commercial setup for single junction cells

In order to measure the spectral response characteristic of a module the SMFB has been equipped with 15 band pass filters in the range of 400 nm to 1100 nm.[9] The SMFB set-up to perform SR spectral response measurements on module level was calibrated with a mono crystalline Si-cell embedded in a standard module, which was initially measured at a PV calibration laboratory.[9] The measured SR characteristics of the a standard crystalline Silicon module performed with the SMFB was in excellent accordance with the measured SR data at a stationary calibration lab, as reported in [9].

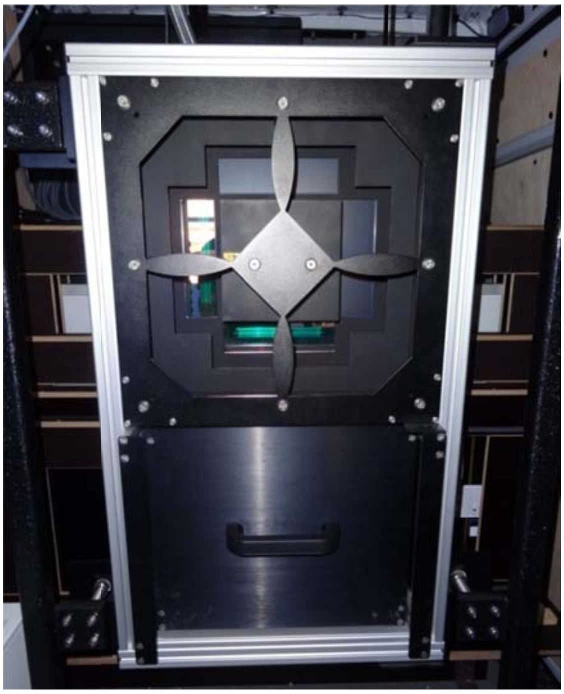

Figure 2: SMFB's commercial flasher (Pasan product) with a box of 15 bandpass filters mounted below the Xenon lamps.

The applied SR measurement method illuminates the total area of the standard module by the monochromatic light, which is transmitted by the selected bandpass filter with each 50nm bandwidth. The filters stored in the box below the Xenon lamps, as shown in Fig. 2, are each placed in front of the Xenon lamps. Thus the DUT monochromatic photocurrent is compared to the test cell photocurrent mounted in the same distance of 5.5 meters to the lamps, just beside the DUT.

2.2 Setup and design of new LED bias-light

The above commercial setup was equipped with a new developed LED back light system. It consists of the first light wall, used as diaphragm next to the Xenon lamps, of infrared LED lights (wavelength 850nm) mounted in a distance of 4.5 meters to the DUT (Fig. 3). The second light wall was equipped with the blue LED (wavelength 470nm) at a distance of 3.85 meter to the DUT. Both the blue and the IR bias-light consist each of about 700 LED's. The developed LED power electronic driver controls the light characteristics within the sub millisecond range independently for each color.

By the grouping of the high number of LED's into single spots, the mounting and orientation of a uniform bias-light was realized in an economic approach. The design of the LED bias-light resulted in four IR spots and eight blue LED spots. The simulation was started from real measurement results of the irradiance distribution of a single LED spotlight. The finally achieved non-uniformity was found to be +/-8.5% both for the blue and the IR LED based on measurement results of the total bias-light.(Fig. 4) However, a higher number of spots will lead to even lower non-uniformity. Each color of the bias-light has the power to generate about 10% of the short circuit current of a standard crystalline silicon solar cell.(Fig. 4) Due to the fact that the electrons in a thin film modules are collected in the size of a cell with a typical length of about 1.5 meter and a width of one centimeter, the uniformity of these LED bias-light strips were calculated, based on the measurement.(Fig. 4) The thin film cell size non-uniformity was found to be +/-2.7% for the IR bias-light while the blue bias-light sum up to maximum +/-5%.

The power electronic is triggered by a photodiode which detecting the flashers light and supply the LED for a few milliseconds at a relatively high current rating.

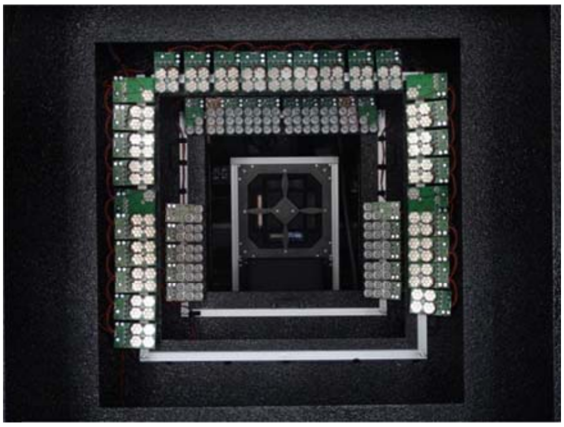

Figure 3: View from the DUT toward the Xenon flasher in the center and the LED bias-light mounted on two different diaphragm walls of the existing light tunnel of

the SMBF with a distance of 4.5 meter for the IR LED and 3.85 meter for the blue LED to the DUT.

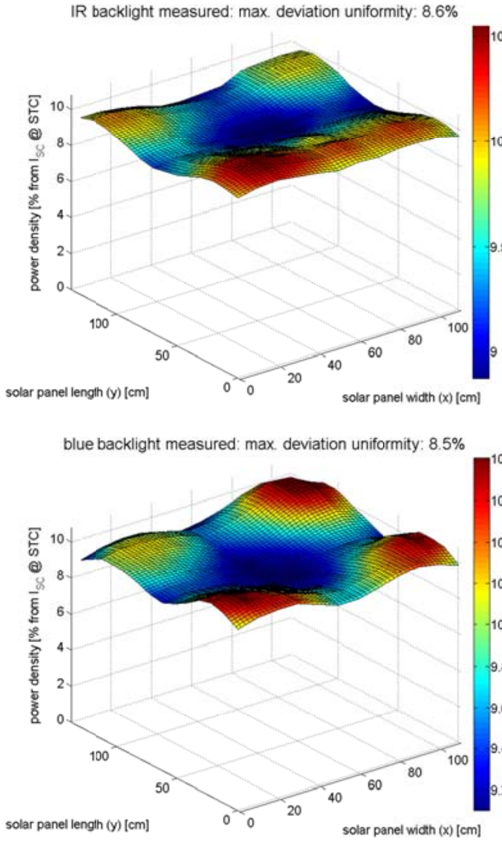

Figure 4: Mapping of the non-uniformity distribution of the LED bias-light in the DUT plane with IR light in the top and blue light in the bottom of the graph.

3 SPECTRAL RESPONSE MEASUREMENT RESULTS of TANDEM MODULES

Two different measurement methods are presented in this chapter to obtain the spectral behavior of a PV tandem module.

3.1 SR Measurement using band pass filters

The SMFB equipped with the flasher and the above described band-pass filters apply a 10ms monochromatic light pulse with a bandwidth of 50nm [8, 9]. Additionally the developed blue 470nm and IR 850nm LED's bias light is activated also across the whole PV module area by an optical trigger. Thus constant blue bias light is turned on during the Xenon flash period and the top cell of the tandem module is saturated by the generated electrons. Under that condition the bottom cell is limiting the total short circuit current of the total tandem module for each monochromatic flash. The SR characteristic of the top cell is activated in the same way using the IR bias light.

The result of the SR measurement of both subcells of a 1.4m^2 a-Si/μc-Si tandem module is shown in Fig. 5 in comparison to a SR measurement of a multi crystalline silicon standard module. The convolution of the subcells SR with the AM 1.5 spectrum resulted in a short circuit current of the bottom cell which is 27% higher compared to the top cells short circuit current. This current ratio was expected for that OC Oerlikon top limited prototype tandem module which was still in the initial non-degraded mode.

Fig. 6 demonstrates that the intensity of the monochromatic flasher light should not be small relative to the LED bias light. Otherwise the bottom cell SR characteristics show an offset behaviour. The reference cell mounting position was done in a way that only the monochromatic flasher light but not the LED bias-light was collected. In Fig. 5 the corrected SR value of Fig. 6 was used.

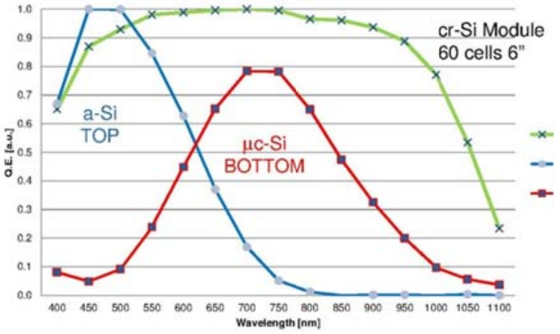

Figure 5: Measured top and bottom spectral response characteristics of a top limited 1.4m^2 a-Si/μc-Si tandem module by the use of the SMFB equipped with bandpass filters and LED (470nm and 850nm) bias light during the flasher light

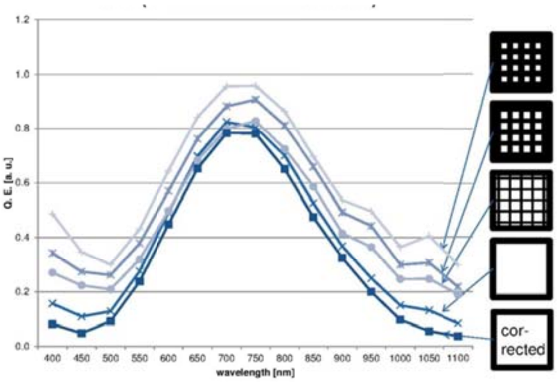

Figure 6: Measured SR of the bottom cell of a 1.4m^2 a-Si/μc-Si module under blue bias light. The different graphs were measured under the same bias light intensity but changing attenuation of the standard monochromatic flasher light.

3.2 Short circuit current at STC flash plus LED bias light

The second method to measure the SR characteristics of a tandem module uses the spectrum of the mobile flasher without the bandpass filters. During the period of 10ms of the constant flasher light at full AM 1.5 spectra a dynamic changing LED bias light was applied. The change of the final short circuit of the DUT is analysed.

Different shapes of the dynamic back light, rectangular or triangle like, different for blue and IR LED light is applied. If only one pattern of both LED characteristic's is found in the tandem module current, we get the information which sub cell is saturated.

Using the same tandem module characterised in Fig.

5 this method was applied at different intensities of AM 1.5 spectrum flashes. Here only the 400W/m2 intensities data is shown. The current measurement was performed by an external DAQ data acquisition unit used instead of the standard Pasan DAQ electronics.

The results of only changing the IR light is shown in Fig.7a while Fig. 7b shows the changes during only changing the blue bias light by a rectangular shape. Finally the current of the tandem module only changes according to Fig. 7b by changing the blue bias light. In both cases the pattern of the constant flasher light plus the rectangular modulated LED light is found in the reference cell of the standard crystalline silicon solar cell.

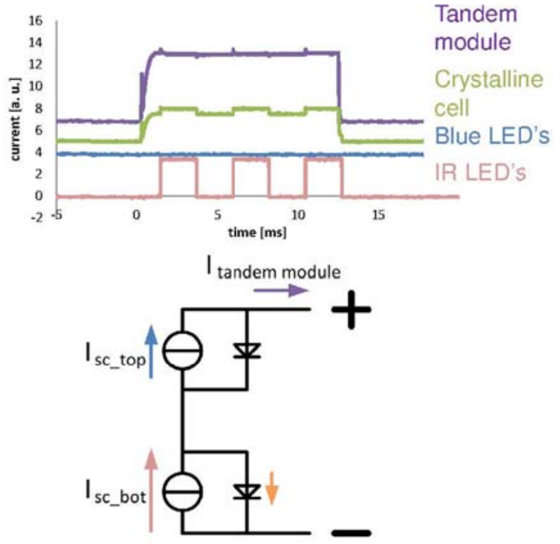

Figure 7a: SMFB short circuit current characteristics of a top limited tandem module (violet) during the flash at 400W/m^2 and additional rectangular characteristics of IR LED bias light.(red) The blue LED was turned off.(blue) The current of an additional standard silicon crystalline reference cell shows the same rectangular pattern (green). In the lower part of the picture the current flow at higher IR bias light is given.

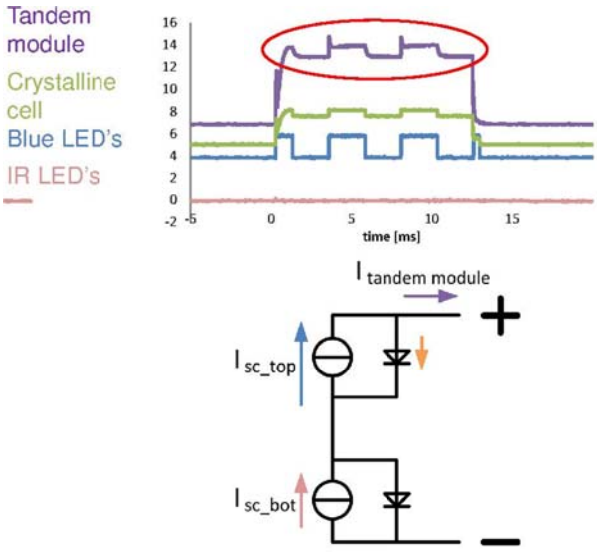

Figure 7b: Same setup and method used like in Fig. 7a but with only changes in blue LED bias-light and without activating the IR LED light.

Thus it is clearly measured in 10ms that this tandem module is top cell limited. The degree of mismatch relative to AM 1.5 can be found in analysing the tandem current characteristic of Fig. 7b. Changes in blue LED bias light by a simple step function resulted in transient capacitive effects of tandem current after the rising edge of LED light during the first millisecond. The same transient slope on IR light did not resulted in such strong transient effects. Other shapes of LED light like sinus and cousins like characteristics will reduce these spikes. The same findings with triangle LED shape found in Fig. 8.

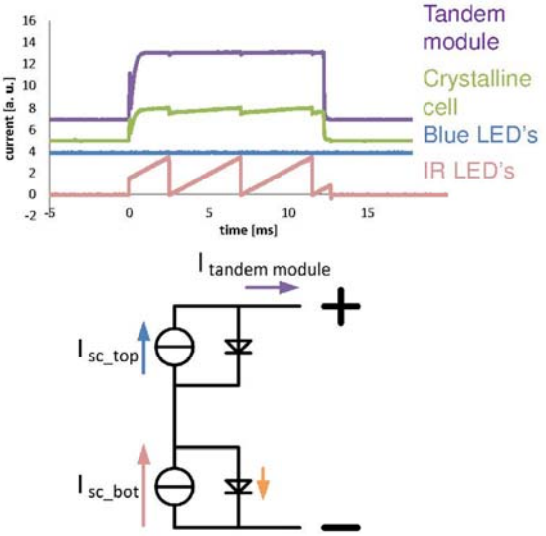

Figure 8a: SMFB short circuit current characteristics of a top limited tandem module (violet) during the flash at 400W/m^2 and additional triangle characteristics of IR LED bias light (see Fig. 7a)

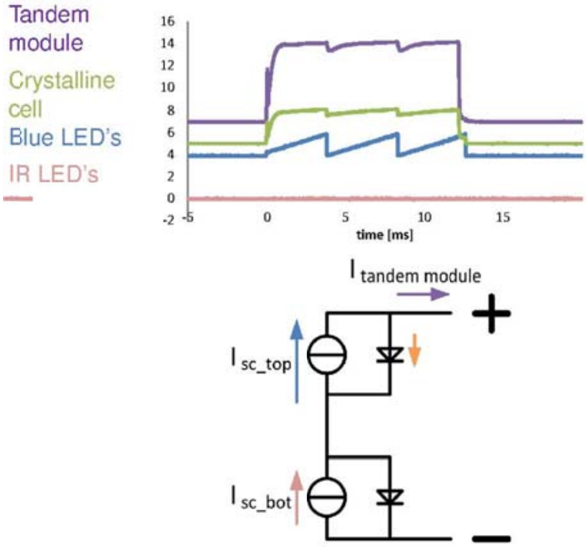

Figure 8b: Same setup and method used like in Fig. 8a but with only changes in blue LED bias-light and without activating the IR LED light

The results in Fig 9 demonstrate that the dynamic LED bias light setup and method may be used also without the AM 1.5 bias light to measure the current matching of top and bottom cells in a few milliseconds.

The instant of time when the maximum of the tandem module current appears within the constant slope of the triangles is a clear measure of top and bottom cell matching factor. The same LED dynamic bias-light can be applied together with the Xenon flasher light comparing to Fig. 7 and 8.

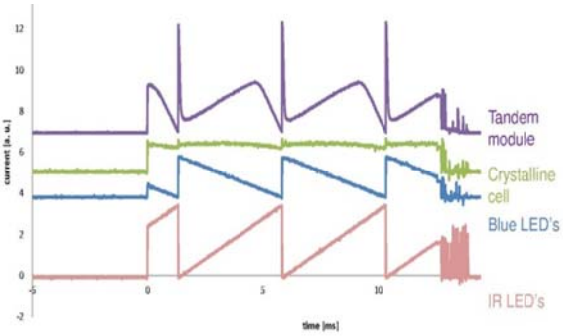

Figure 9: Short circuit current characteristics of a top limited tandem module (violet) under blue and IR bias light but with constant over all photon flux as can be seen by the constant crystalline silicon reference cell current (green) and without using the Xenon lamps flash.

4 CONCLUSION AND OUTLOOK

The implementation of the developed new spectral response measurement techniques of tandem modules was successfully performed on the Swiss Mobile Flasher Bus. A commercial $1.4m^2$ silicon a-Si/µc-Si tandem module was measured at 15 spectral regions from 400nm to 1100nm by the use of optical bandpass filters and the new developed blue and IR LED bias light. By the analysis of the top and bottom cell characteristics it was found that this DUT short circuit current was limited by the top cell.

The same findings resulted in the analysis of the changes of the same DUT short circuit current characteristics during the 10ms Xenon flasher pulse at different dynamic bias light conditions. While the change of the blue bias light was also seen in the DUT short circuit current, in contrast the same changes of IR bias light did not affected the measured tandem current performance. Thus a method is introduced which can be applied in the end test of the tandem modules by the module manufacture to measure the factor of top and bottom cell mismatch within a few milliseconds.

The second approach, to analyse the transient change, of the tandem current by ramping the LED bias light in a triangle shape or rectangular or each other characteristics like sine or cosine, allows successfully, verifying which sub cell is limiting to what amount.

Future work is planned to modulate the constant Xenon light during regular IV curve measurement with the dynamic LED blue and IR bias light. This may be either done by sinus and cosine characteristics or even increasing amplitudes of sine/cosine during the flash or other shapes. This LED setup in principle has the potential to be retrofitted to every standard flasher offering dynamic backlight without effecting the existing electronics or data acquisition.

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